ASHRAE POCKET GUIDE

for Air Conditioning, Heating, Ventilation, Refrigeration

SI

9th Edition

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PREFACE

The ASHRAE Pocket Guide was developed to serve as a ready, offline reference for engineers without easy access to complete ASHRAE Handbook volumes.

This ninth edition has been revised for 2017 to include updates from current editions of the ASHRAE Handbook series as well as from various ASHRAE standards. This edition also features a renewed emphasis in basic design aids: content on more specialized system types has been replaced by an appendix containing climatic design data for selected worldwide locations.

This edition of the ASHRAE Pocket Guide, which was first published in 1987, was compiled by ASHRAE staff editors; previous major contributors were Carl W. MacPhee, Griffith C. Burr, Jr., Harry E. Rountree, and Frederick H. Kohloss.

Throughout this Pocket Guide, original sources of figures and tables are indicated where applicable. For space concerns, a shorthand for ASHRAE publications has been adopted. ASHRAE sources are noted after figure captions or table titles in brackets using the following abbreviations:

Fig	Figure
Tbl	Table
Ch	Chapter
Std	ASHRAE Standard
2017F, 2013F, etc	*ASHRAE Handbook—Fundamentals*
2016S, 2012S, etc.	*ASHRAE Handbook—HVAC Systems and Equipment*
2015A, 2011A, etc.	*ASHRAE Handbook—HVAC Applications*
2014R, 2010R, etc.	*ASHRAE Handbook—Refrigeration*

Complete entries for all references cited in tables and figures are available in the original source publications.

1. AIR HANDLING AND PSYCHROMETRICS

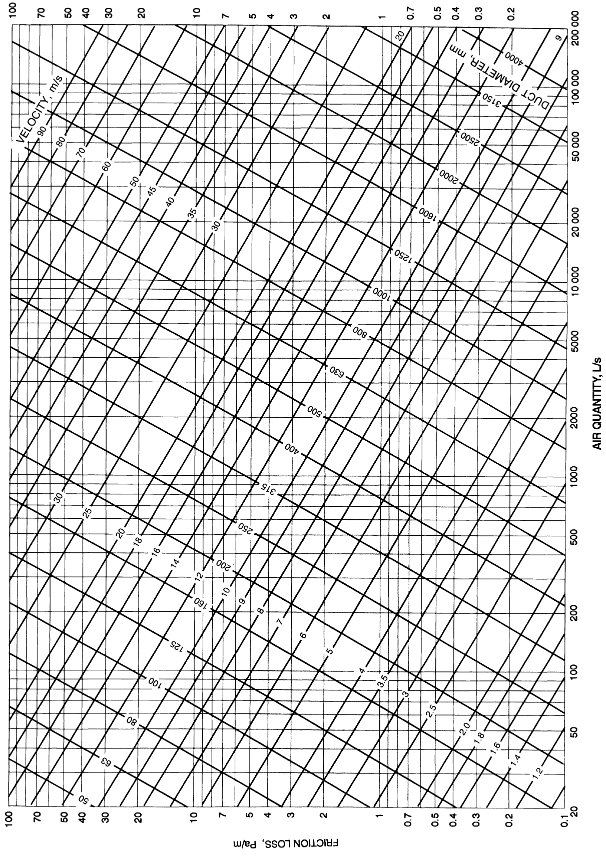


Figure 1.1 Friction Chart for Round Duct (ρ = 1.20 kg/m^3 and ε = 0.09 mm)
[2017F, Ch 21, Fig 10]

Table 1.1 Velocities vs. Velocity Pressures

Velocity V, m/s	Velocity Pressure P_v, Pa
1.0	0.6
2.0	2.4
3.0	5.4
4.0	9.6
5.0	15.1
5.5	18.3
6.0	21.7
6.5	25.5
7.0	29.5
7.5	33.9
8.0	38.5
8.5	43.5
9.0	48.8
9.5	54.3
10.0	60.2
11.0	72.9
12.0	86.7
13.0	101.8
14.0	118.0
15.0	135
17.5	184
20.0	241
22.5	305
25.0	376

$P_v = 0.602\ V^2$

Noncircular Ducts

Hydraulic diameter $D_h = 4A/P$, where A = duct area (mm) and P = perimeter (mm). Ducts having the same hydraulic diameter will have approximately the same fluid resistance at equal velocities.

Fittings

Resistance to flow through fittings can be expressed by fitting loss coefficients C. The friction loss in a fitting in inches of water is CP_v. The more radically the airflow is changed in direction or velocity, the greater the fitting loss coefficient. See *ASHRAE Duct Fitting Database* for a complete list. 90° mitered elbows with vanes will usually have C between 0.11 and 0.33.

Round Flexible Ducts

Nonmetallic flexible ducts fully extended have friction losses approximately three times that of galvanized steel ducts. This rises rapidly for unextended ducts by a correction factor of 4 if 70% extended, 3 if 80% extended, and 2 if 90% extended. For centerline bend radius ratio to diameter of 1 to 4, the approximate loss coefficient is between 0.82 and 0.87.

Table 1.2 Duct Leakage Classification[a]

Duct Type	Sealed[b,c]		Unsealed[c]	
	Predicted Leakage Class C_L	Leakage Rate, L/(s·m^2) at 250 Pa	Predicted Leakage Class C_L	Leakage Rate, L/(s·m^2) at 250 Pa
Metal (flexible excluded)				
Round and flat oval	4	0.14	42	1.5
			(8 to 99)	(0.3 to 3.6)
Rectangular				
≤500 Pa	17	0.62	68	2.5
(both positive and negative pressures)			(17 to 155)	(0.6 to 5.6)
>500 and ≤2500 Pa	8	0.29	68	2.5
(both positive and negative pressures)			(17 to 155)	(0.6 to 5.6)
Flexible				
Metal, aluminum	11	0.40	42	1.5
			(17 to 76)	(0.6 to 2.8)
Nonmetal	17	0.62	30	1.5
			(6 to 76)	(0.2 to 2.8)
Fibrous glass				
Round	4	0.14	na	na
Rectangular	8	0.29	na	na

[a] The leakage classes listed in this table are averages based on tests conducted by AISI/ SMACNA (1972), ASHRAE/SMACNA/TIMA (1985), and Swim and Griggs (1995).

[b] The leakage classes listed in the sealed category are based on the assumptions that for metal ducts, all transverse joints, seams, and openings in the duct wall are sealed at pressures over 750 Pa, that transverse joints and longitudinal seams are sealed at 500 and 750 Pa, and that transverse joints are sealed below 500 Pa. Lower leakage classes are obtained by careful selection of joints and sealing methods.

[c] Leakage classes assigned anticipate about 0.82 joints per metre of duct. For systems with a high fitting to straight duct ratio, greater leakage occurs in both the sealed and unsealed conditions.

Table 1.3 Recommended Ductwork Leakage Class by Duct Type

Duct Type	Leakage Class C_L	Leakage Rate, L/(s·m^2) at 250 Pa
Metal		
Round	4	0.14
Flat oval	4	0.14
Rectangular	8	0.29
Flexible	8	0.29
Fibrous glass		
Round	4	0.14
Rectangular	8	0.29

$$\text{Leakage Class } C_L = Q/\Delta P_S^{0.65} \tag{1.1}$$

where

Q = leakage rate, L/s/100 m^2 surface area

ΔP_s = static pressure difference, Pa between inside and outside of duct

Table 1.4 Duct Sealing Requirement Levels

Duct Seal Level	Sealing Requirements[a]
A	All transverse joints, longitudinal seams, and duct wall penetrations
B	All transverse joints and longitudinal seams
C	Transverse joints only

[a] Transverse joints are connections of two duct or fitting elements oriented perpendicular to flow. Longitudinal seams are joints oriented in the direction of airflow. Duct wall penetrations are openings made by screws, non-self-sealing fasteners, pipe, tubing, rods, and wire. Round and flat oval spiral lock seams need not be sealed prior to assembly, but may be coated after assembly to reduce leakage. All other connections are considered transverse joints, including but not limited to spin-ins, taps and other branch connections, access door frames, and duct connections to equipment.

Table 1.5 Duct Sealing Recommendations

Recommended Duct Seal Levels	Duct Type			
	Supply			
Duct Location	≤500 Pa of water	>500 Pa of water	Exhaust	Return
Outdoors	A	A	A	A
Unconditioned spaces	B	A	B	B
Conditioned spaces (concealed ductwork)	C	B	B	C
Conditioned spaces (exposed ductwork)	A	A	B	B

Table 1.6 Duct Leakage per Unit Length

Unsealed Longitudinal Seam Leakage, Metal Ducts		Leakage, L per metre Seam Length at 250 Pa Static Pressure	
Type of Duct/Seam		Range	Average
Rectangular	Pittsburgh lock		
	26 gage	0.015 to 0.03	0.025
	22 gage	0.0015 to 0.003	0.0025
	Button punch snaplock		
	26 gage	0.05 to 0.23	0.12
	22 gage	NA (1 test)	0.005
Round	Spiral (26 gage)	NA (1 test)	0.023
	Snaplock	0.06 to 0.22	0.17
	Grooved	0.17 to 0.28	0.19

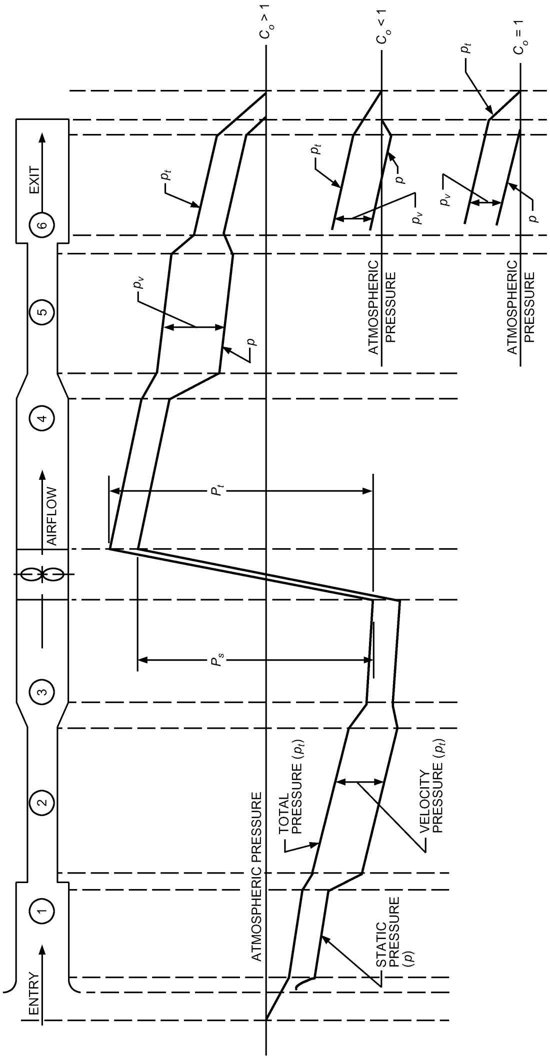


Figure 1.2 At Exit, the Fitting Coefficient C_o Affects ρ_t Loss [2017F, Ch 21, Fig 7]

Table 1.7 Circular Equivalents of Rectangular Duct for Equal Friction and Capacity[a]

Lgth.	Length of One Side of Rectangular Duct (a), mm																			
Adj.[b]	100	125	150	175	200	225	250	275	300	350	400	450	500	550	600	650	700	750	800	900
100	109																			
150	133	150	164																	
200	152	172	189	204	219															
250	169	190	210	228	244	259	273													
300	183	207	229	248	266	283	299	314	328											
400	207	235	260	283	305	325	343	361	378	409	437									
500	227	258	287	313	337	360	381	401	420	455	488	518	547							
600	245	279	310	339	365	390	414	436	457	496	533	567	598	628	656					
700	261	298	331	362	391	418	443	467	490	533	573	610	644	677	708	737	765			
800	275	314	350	383	414	442	470	496	520	567	609	649	687	722	755	787	818	847	875	
900	289	330	367	402	435	465	494	522	548	597	643	686	726	763	799	833	866	897	927	984
1000	301	344	384	420	454	486	517	546	574	626	674	719	762	802	840	876	911	944	976	1037
1200	324	370	413	453	490	525	558	590	620	677	731	780	827	872	914	954	993	1030	1066	1133
1400	344	394	439	482	522	559	595	629	662	724	781	835	886	934	980	1024	1066	1107	1146	1220
1600	362	415	463	508	551	591	629	665	700	766	827	885	939	991	1041	1088	1133	1177	1219	1298
1800	379	434	485	533	577	619	660	698	735	804	869	930	988	1043	1096	1146	1195	1241	1286	1371
2000	395	453	506	555	602	646	688	728	767	840	908	973	1034	1092	1147	1200	1252	1301	1348	1438
2200	410	470	525	577	625	671	715	757	797	874	945	1013	1076	1137	1195	1251	1305	1356	1406	1501
2400	424	486	543	597	647	695	740	784	826	905	980	1050	1116	1180	1241	1299	1355	1409	1461	1561
2600	437	501	560	616	688	717	764	810	853	935	1012	1085	1154	1220	1283	1344	1402	1459	1513	1617
2800	450	516	577	634	688	738	787	834	879	964	1043	1119	1190	1259	1324	1387	1447	1506	1562	1670

Table 1.7 Circular Equivalents of Rectangular Duct for Equal Friction and Capacity[a] *(Continued)*

Lgth. Adj.[b]	Length of One Side of Rectangular Duct (*a*), mm																			
	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	2500	2600	2700	2800	2900
1000	1093																			
1100	1146	1202																		
1200	1196	1256	1312																	
1300	1244	1306	1365	1421																
1400	1289	1354	1416	1475	1530															
1500	1332	1400	1464	1526	1584	1640														
1600	1373	1444	1511	1574	1635	1693	1749													
1700	1413	1486	1555	1621	1684	1745	1803	1858												
1800	1451	1527	1598	1667	1732	1794	1854	1912	1968											
1900	1488	1566	1640	1710	1778	1842	1904	1964	2021	2077										
2000	1523	1604	1680	1753	1822	1889	1952	2014	2073	2131	2186									
2100	1558	1640	1719	1793	1865	1933	1999	2063	2124	2183	2240	2296								
2200	1591	1676	1756	1833	1906	1977	2044	2110	2173	2233	2292	2350	2405							
2300	1623	1710	1793	1871	1947	2019	2088	2155	2220	2283	2343	2402	2459	2514						
2400	1655	1744	1828	1909	1986	2060	2131	2200	2266	2330	2393	2453	2511	2568	2624					
2500	1685	1776	1862	1945	2024	2100	2173	2243	2311	2377	2441	2502	2562	2621	2678	2733				
2600	1715	1808	1896	1980	2061	2139	2213	2285	2355	2422	2487	2551	2612	2672	2730	2787	2842			
2700	1744	1839	1929	2015	2097	2177	2253	2327	2398	2466	2533	2598	2661	2722	2782	2840	2896	2952		
2800	1772	1869	1961	2048	2133	2214	2292	2367	2439	2510	2578	2644	2708	2771	2832	2891	2949	3006	3061	
2900	1800	1898	1992	2081	2167	2250	2329	2406	2480	2552	2621	2689	2755	2819	2881	2941	3001	3058	3115	3170

[a] Table based on $D_e = 1.30\,(ab)^{0.625}/(a+b)^{0.25}$.
[b] Length of adjacent side of rectangular duct (b), mm.

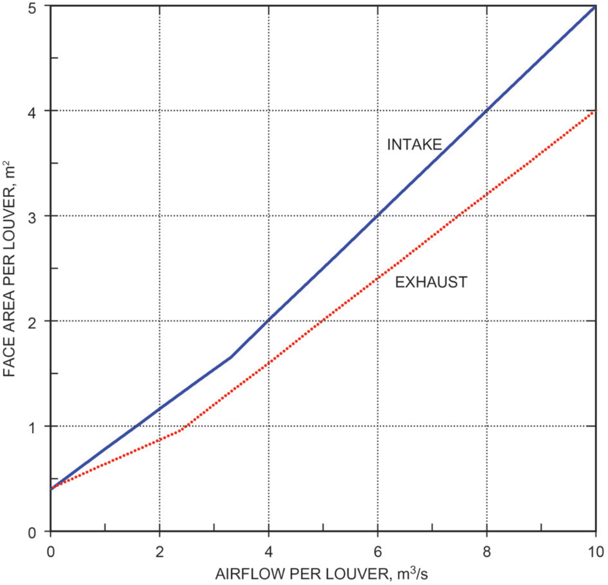
Table 1.8 Equivalent Flat Oval Duct Dimensions* [2017F, Ch 21, Tbl 3]

Circular Duct Diameter, mm	Minor Axis *a*, mm																
	70	100	125	150	175	200	250	275	300	325	350	375	400	450	500	550	600
	Major Axis *A*, mm																
125	205																
140	265	180															
160	360	235	190														
180	475	300	235	200													
200		380	290	245	215												
224		490	375	305	—	240											
250			475	385	325	290											
280				485	410	360	—	285									
315				635	525	—	—	345	325								
355				840	—	580	460	425	395	375							
400				1115	—	760	—	530	490	460	435						
450				1490	—	995	—	675	—	570	535	505					
500						1275	—	845	—	700	655	615	580				
560						1680	—	1085	—	890	820	765	720				
630								1425	—	1150	1050	970	905	810			
710										1505	1370	1260	1165	1025			
800											1800	1645	1515	1315	1170	1065	
900												2165	1985	1705	1500	1350	
1000														2170	1895	1690	
1120															2455	2170	1950
1250																2795	2495

* Table based on $D_e = 1.30\,(ab)^{0.625}/(a + b)^{0.25}$.

Table 1.9 Typical Design Velocities for HVAC Components

Duct Element	Face Velocity, m/s
Louvers	
Intake	
7000 cfm3300 L/s and greater	2
Less than 7000 cfm3300 L/s	See Figure 1.3
Exhaust	
5000 cfm2400 L/s and greater	2.5
Less than 5000 cfm2400 L/s	See Figure 1.3
Filters	
Panel filters	
Viscous impingement	1 to 4
Dry-type, extended-surface	
Flat (low efficiency)	Duct velocity
Pleated media (intermediate efficiency)	Up to 3.8
HEPA	1.3
Renewable media filters	
Moving-curtain viscous impingement	2.5
Moving-curtain dry media	1
Electronic air cleaners	
Ionizing type	0.8 to 1.8
Heating Coils	
Steam and hot water	2.5 to 5
	1 min., 8 max.
Electric	
Open wire	Refer to mfg. data
Finned tubular	Refer to mfg. data
Dehumidifying Coils	2 to 3
Air Washers	
Spray type	Refer to mfg. data
Cell type	Refer to mfg. data
High-velocity spray type	6 to 9



Parameters Used to Establish Figure	Intake Louver	Exhaust Louver
Minimum free area (1220 mm square test section), %	45	45
Water penetration, $mL/(m^2 \cdot 0.25\ h)$	Negligible (less than 0.3)	N/A
Maximum static pressure drop, Pa	35	60

Figure 1.3 Criteria for Louver Sizing [2017F, Ch 21, Fig 19]

Table 1.10 Fan Laws[a,b]

For All Fan Laws: $\eta_{t1} = \eta_{t2}$ and (point of rating)$_1$ = (point of rating)$_2$

No.	Dependent Variables	Independent Variables	
1a	$Q_1 = Q_2$	$\times \left(\frac{D_1}{D_2}\right)^3 \times \frac{N_1}{N_2}$	$\times 1$
1b	Pressure$_1$ = Pressure$_2$[c]	$\times \left(\frac{D_1}{D_2}\right)^2 \times \left(\frac{N_1}{N_2}\right)^2$	$\times \frac{\rho_1}{\rho_2}$
1c	$W_1 = W_2$	$\times \left(\frac{D_1}{D_2}\right)^5 \times \left(\frac{N_1}{N_2}\right)^3$	$\times \frac{\rho_1}{\rho_2}$
2a	$Q_1 = Q_2$	$\times \left(\frac{D_1}{D_2}\right)^2 \times \left(\frac{\text{Press.}_1}{\text{Press.}_2}\right)^{1/2}$	$\times \left(\frac{\rho_2}{\rho_1}\right)^{1/2}$
2b	$N_1 = N_2$	$\times \left(\frac{D_2}{D_1}\right) \times \left(\frac{\text{Press.}_1}{\text{Press.}_2}\right)^{1/2}$	$\times \left(\frac{\rho_2}{\rho_1}\right)^{1/2}$
2c	$W_1 = W_2$	$\times \left(\frac{D_1}{D_2}\right)^2 \times \left(\frac{\text{Press.}_1}{\text{Press.}_2}\right)^{3/2}$	$\times \left(\frac{\rho_2}{\rho_1}\right)^{1/2}$
3a	$N_1 = N_2$	$\times \left(\frac{D_2}{D_1}\right)^3 \times \frac{Q_1}{Q_2}$	$\times 1$
3b	Pressure$_1$ = Pressure$_2$	$\times \left(\frac{D_2}{D_1}\right)^4 \times \left(\frac{Q_1}{Q_2}\right)^2$	$\times \frac{\rho_1}{\rho_2}$
3c	$W_1 = W_2$	$\times \left(\frac{D_2}{D_1}\right)^4 \times \left(\frac{Q_1}{Q_2}\right)^3$	$\times \frac{\rho_1}{\rho_2}$

a. The subscript 1 denotes that the variable is for the fan under consideration.

b. The subscript 2 denotes that the variable is for the tested fan.

c. Fan total pressure P_{tf}, fan velocity pressure P_{vf}, or fan static pressure P_{sf}.

Unless otherwise identified, fan performance data are based on dry air at standard conditions 101.325 kPa and 20°C (1.204 kg/m^3). In actual applications, the fan may be required to handle air or gas at some other density. The change in density may be because of temperature, composition of the gas, or altitude. As indicated by the Fan Laws, the fan performance is affected by gas density. With constant size and speed, the horsepower and pressure varies directly as the ratio of gas density to the standard air density.

The application of the Fan Laws for a change in fan speed N for a specific size fan is shown in Figure 1.4. The computed P_t curve is derived from the base curve. For example, point E(N_1 = 650) is computed from point D(N_2= 600) as follows:

At D,

$$Q_2 = 3 \text{ m}^3\text{/s and } P_{tf_2} = 228 \text{ Pa} \tag{1.2}$$

Using Fan Law 1a at Point E

$$Q_1 = 3 \times 650/600 = 3.25 \text{ m}^3\text{/s} \tag{1.3}$$

Using Fan Law 1b

$$P_{tf_1} = 228 \times (650/600)^2 = 268 \text{ Pa} \tag{1.4}$$

The completed P_{tf_1}, N = 650 curve thus may be generated by computing additional points from data on the base curve, such as point G from point F.

$$\text{fan power, kW} = \frac{\text{L/s} \times \text{pressure difference, kPa}}{40350 \times \text{fan efficiency} \times \text{motor efficiency}} \tag{1.5}$$

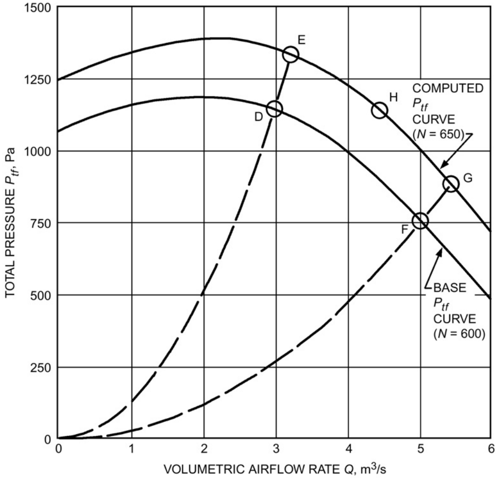


Figure 1.4 Example Calculation of Fan Laws [2016S, Ch 21, Fig 4]

Table 1.11 Types of Fans [2016S, Ch 21, Tbl 1]

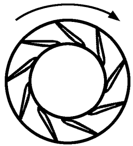
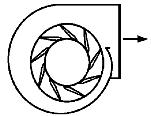
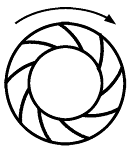
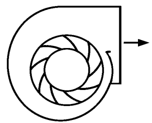
	Type	Impeller Design		Housing Design		Performance Characteristics	Applications
Centrifugal Fans	Airfoil		• Blades of airfoil contour curved away from direction of rotation. Deep blades allow efficient expansion within blade passages. • Air leaves impeller at velocity less than tip speed. • For given duty, has highest speed of centrifugal fan designs.		• Scroll design for efficient conversion of velocity pressure to static pressure. • Maximum efficiency requires close clearance and alignment between wheel and inlet.	• Highest efficiency of all centrifugal fan designs and peak efficiencies occur at 50 to 60% of wide-open volume. • Fan has a non-overloading characteristic, which means power reaches maximum near peak efficiency and becomes lower, or self-limiting, toward free delivery.	• General heating, ventilating, and air-conditioning applications. • Usually only applied to large systems, which may be low-, medium-, or high-pressure applications. • Applied to large, clean-air industrial operations for significant energy savings.
	Backward-Inclined Backward-Curved		• Single-thickness blades curved or inclined away from direction of rotation. • Efficient for same reasons as airfoil fan.		• Uses same housing configuration as airfoil design.	• Similar to airfoil fan, except peak efficiency slightly lower. • Curved blades are slightly more efficient than straight blades.	• Same heating, ventilating, and air-conditioning applications as airfoil fan. • Used in some industrial applications where environment may corrode or erode airfoil blade.

Table 1.11 Types of Fans [2016S, Ch 21, Tbl 1] ***(Continued)***

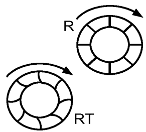
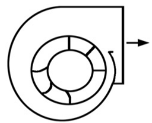
	Type	Impeller Design		Housing Design		Performance Characteristics	Applications
Centrifugal Fans (continued)	Radial (R) Radial Tip (Rt)		• Higher pressure characteristics than airfoil, backward-curved, and backward-inclined fans. • Curve may have a break to left of peak pressure.		• Scroll similar to and often identical to other centrifugal fan designs. • Fit between wheel and inlet not as critical as for airfoil and backward-inclined fans.	• Higher pressure characteristics than airfoil and backward-curved fans. • Pressure may drop suddenly at left of peak pressure, but this usually causes no problems. • Power rises continually to free delivery, which is an overloading characteristic. • Curved blades are slightly more efficient than straight blades.	• Primarily for materials handling in industrial plants. Also for some high-pressure industrial requirements. • Rugged wheel is simple to repair in the field. Wheel sometimes coated with special material. • Not common for HVAC applications.

Table 1.11 Types of Fans [2016S, Ch 21, Tbl 1] ***(Continued)***

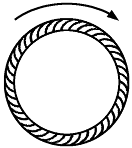
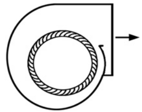
	Type	Impeller Design		Housing Design		Performance Characteristics	Applications
Centrifugal Fans (continued)	Forward-Curved		• Flatter pressure curve and lower peak efficiency than the airfoil, backward-curved, and backward-inclined.		• Scroll similar to and often identical to other centrifugal fan designs. • Fit between wheel and inlet not as critical as for airfoil and backward-inclined fans.	• Pressure curve less steep than that of backward-curved fans. Curve dips to left of peak pressure. • Highest efficiency occurs at 40 to 50% of wide-open volume. • Operate fan to right of peak pressure. Use caution when selecting left of peak pressure, because instability is possible. • Power rises continually to free delivery which is an overloading characteristic.	• Primarily for low-pressure HVAC applications, such as residential furnaces, central station units, and packaged air conditioners.

Table 1.11 Types of Fans [2016S, Ch 21, Tbl 1] ***(Continued)***

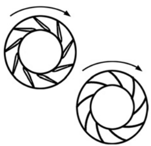
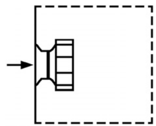
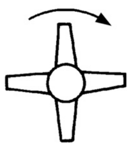
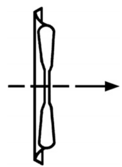
	Type	Impeller Design		Housing Design		Performance Characteristics	Applications
Centrifugal Fans (continued)	Plenum/ Plug		• Plenum and plug fans typically use airfoil, backward inclined, or backward curved impellers in a single inlet configuration. Relative benefits of each impeller are the same as those described for scroll housed fans.		• Plenum and plug fans are unique in that they operate with no housing. The equivalent of a housing, or plenum chamber (dashed line), depends on the application. • The components of the drive system for the plug fan are located outside the airstream.	• Plenum and plug fans are similar to comparable housed airfoil/backward-curved fans but are generally less efficient because of inefficient conversion of kinetic energy in discharge airstream. • They are more susceptible to performance degradation caused by poor installation.	• Plenum and plug fans are used in a variety of HVAC applications such as air handlers, especially where direct-drive arrangements are desirable. • Other advantages of these fans are discharge configuration flexibility and potential for smaller-footprint units.
Axial Fans	Propeller		• Low efficiency. • Limited to low-pressure applications. • Usually low-cost impellers have two or more blades of single thickness attached to relatively small hub. • Primary energy transfer by velocity pressure.		• Simple circular ring, orifice plate, or venturi. • Optimum design is close to blade tips and forms smooth airfoil into wheel.	• High flow rate, but very low pressure capabilities. • Maximum efficiency reached near free delivery. • Discharge pattern circular and airstream swirls.	• For low-pressure, high-volume air-moving applications, such as air circulation in a space or ventilation through a wall without ductwork. • Used for makeup air applications.

Table 1.11 Types of Fans [2016S, Ch 21, Tbl 1] ***(Continued)***

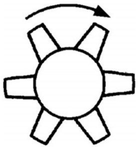
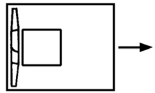
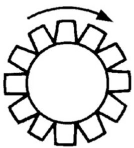
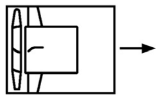
	Type	Impeller Design		Housing Design		Performance Characteristics	Applications
Axial Fans (continued)	Tubeaxial		• Somewhat more efficient and capable of developing more useful static pressure than propeller fan. • Usually has 4 to 8 blades with airfoil or single- thickness cross section. • Hub is usually less than half the fan tip diameter.		• Cylindrical tube with close clearance to blade tips.	• High flow rate, medium pressure capabilities. • Pressure curve dips to left of peak pressure. Avoid operating fan in this region. • Discharge pattern circular and airstream rotates or swirls.	• Low- and medium-pressure ducted HVAC applications where air distribution downstream is not critical. • Used in some industrial applications, such as drying ovens, paint spray booths, and fume exhausts.
	Vaneaxial		• Good blade design gives medium- to high-pressure capability at good efficiency. • Most efficient have airfoil blades. • Blades may have fixed, adjustable, or controllable pitch. • Hub is usually greater than half fan tip diameter.		• Cylindrical tube with close clearance to blade tips. • Guide vanes upstream or downstream from impeller increase pressure capability and efficiency.	• High-pressure characteristics with medium-volume flow capabilities. • Pressure curve dips to left of peak pressure. Avoid operating fan in this region. • Guide vanes correct circular motion imparted by impeller and improve pressure characteristics and efficiency of fan.	• General HVAC systems in low-, medium-, and high-pressure applications where straight-through flow and compact installation are required. • Has good downstream air distribution. • Used in industrial applications in place of tubeaxial fans. • More compact than centrifugal fans for same duty.

Table 1.11 Types of Fans [2016S, Ch 21, Tbl 1] ***(Continued)***

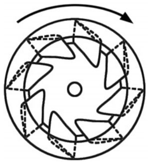
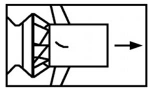
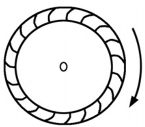
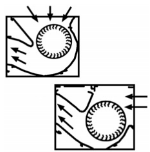
	Type	Impeller Design		Housing Design		Performance Characteristics	Applications
Mixed-Flow	Mixed-Flow		• Combination of axial and centrifugal characteristics. Ideally suited in applications in which the air has to flow in or out axially. Higher pressure characteristic than axial fans.		• The majority of mixed-flow fans are in a tubular housing and include outlet turning vanes. • Can operate without housing or in a pipe and duct.	• Characteristic pressure curve between axial fans and centrifugal fans. Higher pressure than axial fans and higher volume flow than centrifugal fans.	• Similar HVAC applications to centrifugal fans or in applications where an axial fan cannot generate sufficient pressure rise.
Cross-Flow	Cross-Flow (Tangential)		• Impeller with forward-curved blades. During rotation the flow of air passes through part of the rotor blades into the rotor. This creates an area of turbulence which, working with the guide system, deflects the airflow through another section of the rotor into the discharge duct of the fan casing. Lowest efficiency of any type of fan.		• Special designed housing for 90°or straight through airflow.	• Similar to forward-curved fans. Power rises continually to free delivery, which is an overloading characteristic. • Unlike all other fans, performance curves include motor characteristics. • Lowest efficiency of any fan type.	• Low-pressure HVAC systems such as fan heaters, fireplace inserts, electronic cooling, and air curtains.

Table 1.11 Types of Fans [2016S, Ch 21, Tbl 1] *(Continued)*

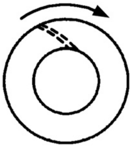
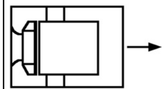
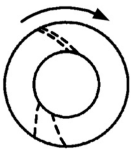
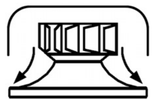
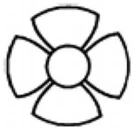
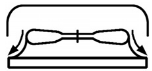
	Type	Impeller Design		Housing Design		Performance Characteristics	Applications
Other Designs	Tubular Centrifugal		• Performance similar to backward-curved fan except capacity and pressure are lower. • Lower efficiency than backward-curved fan. • Performance curve may have a dip to the left of peak pressure.		• Cylindrical tube similar to vaneaxial fan, except clearance to wheel is not as close. • Air discharges radially from wheel and turns 90° to flow through guide vanes.	• Performance similar to backward-curved fan, except capacity and pressure are lower. • Lower efficiency than backward-curved fan because air turns 90°. • Performance curve of some designs is similar to axial flow fan and dips to left of peak pressure.	• Primarily for low-pressure, return air systems in HVAC applications. • Has straight-through flow.
Other Designs	Power Roof Ventilators — Centrifugal		• Low-pressure exhaust systems such as general factory, kitchen, warehouse, and some commercial installations. • Provides positive exhaust ventilation, which is an advantage over gravity-type exhaust units. • Centrifugal units are slightly quieter than axial units.		• Normal housing not used, because air discharges from impeller in full circle. • Usually does not include configuration to recover velocity pressure component.	• Usually operated without ductwork; therefore, operates at very low pressure and high volume.	• Centrifugal units are somewhat quieter than axial flow units. • Low-pressure exhaust systems, such as general factory, kitchen, warehouse, and some commercial installations. • Low first cost and low operating cost give an advantage over gravity-flow exhaust systems.

Table 1.11 Types of Fans [2016S, Ch 21, Tbl 1] ***(Continued)***

	Type		Impeller Design		Housing Design		Performance Characteristics	Applications
Other Designs (continued)	Power Roof Ventilators (continued)	Axial		• Low-pressure exhaust systems such as general factory, kitchen, warehouse, and some commercial installations. • Provides positive exhaust ventilation, which is an advantage over gravity-type exhaust units. • Hood protects fan from weather and acts as safety guard.		• Essentially a propeller fan mounted in a supporting structure. • Air discharges from annular space at bottom of weather hood.	• Usually operated without ductwork; therefore, operates at very low pressure and high volume.	• Low-pressure exhaust systems, such as general factory, kitchen, warehouse, and some commercial installations. • Low first cost and low operating cost give an advantage over gravity-flow exhaust systems.

Fan System Effect

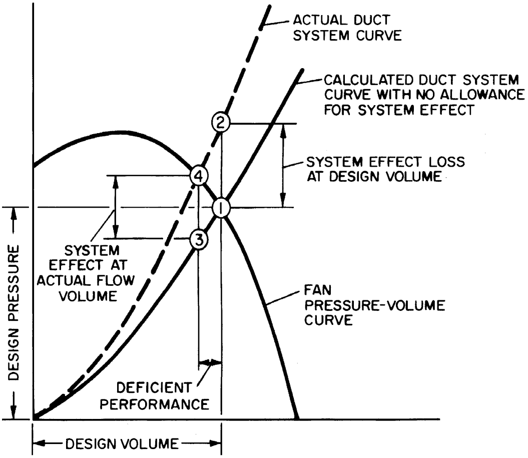


Figure 1.5 Deficient Fan/System Performance

Figure 1.5 illustrates deficient fan/system performance. System pressure losses have been determined accurately, and a fan has been selected for operation at point 1. However, no allowance has been made for the effect of system connections to the fan on fan performance. To compensate, a fan system effect must be added to the calculated system pressure losses to determine the actual system curve. The point of intersection between the fan performance curve and the actual system curve is point 4. The actual flow volume is, therefore, deficient by the difference from 1 to 4. To achieve design flow volume, a fan system effect pressure loss equal to the pressure difference between points 1 and 2 should be added to the calculated system pressure losses, and the fan should be selected to operate at point 2.

For rated performance, air must enter a fan uniformly over the inlet area in an axial direction without prerotation.

Fans within plenums and cabinets or next to walls should be located so that air may flow unobstructed into the inlets.

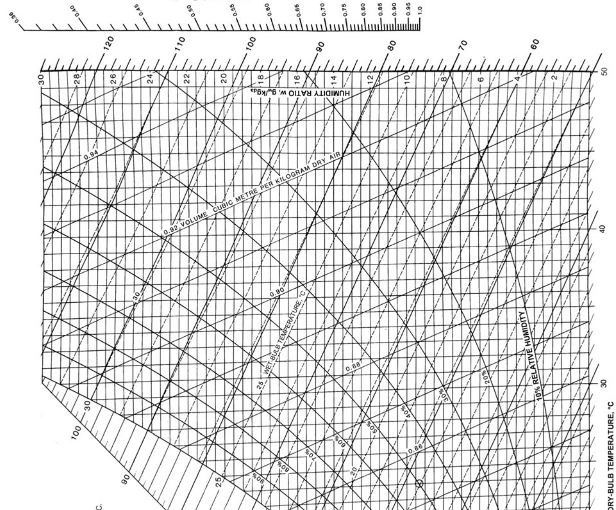


Figure 1.6 Psychrometric Chart for Normal Temperature, Sea Level [2017F, Ch 1, Fig 1]

Air-Conditioning Processes

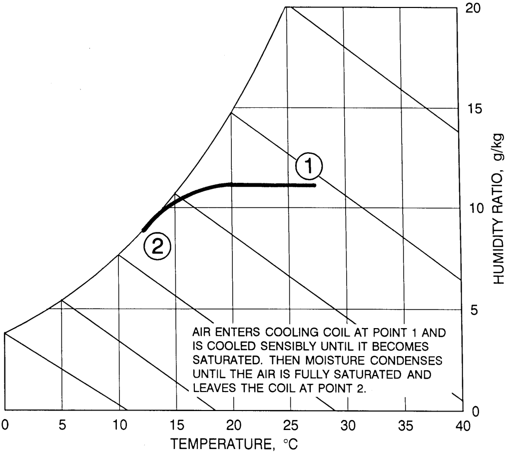
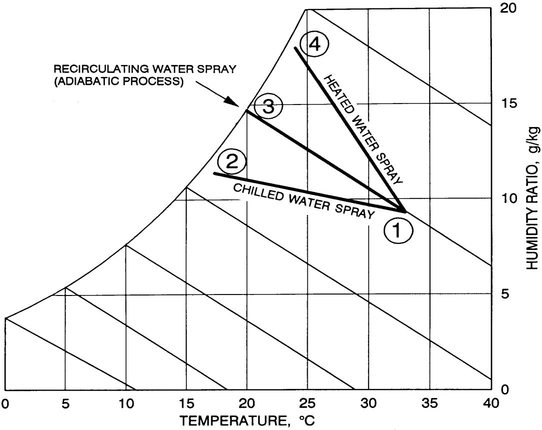
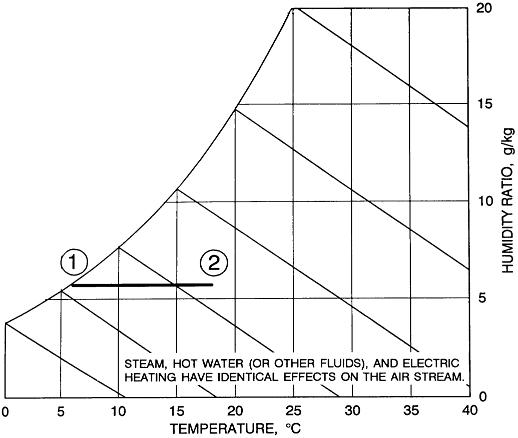


Figure 1.7 Direct Expansion or Chilled Water Cooling and Dehumidification



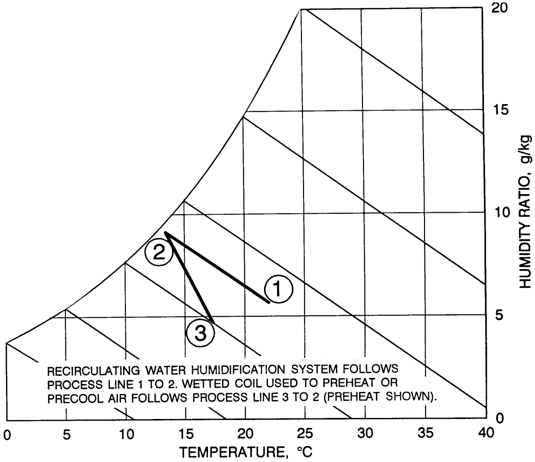
Water Spray Cooling

Figure 1.8 Direct Expansion or Chilled Water Cooling and Dehumidification



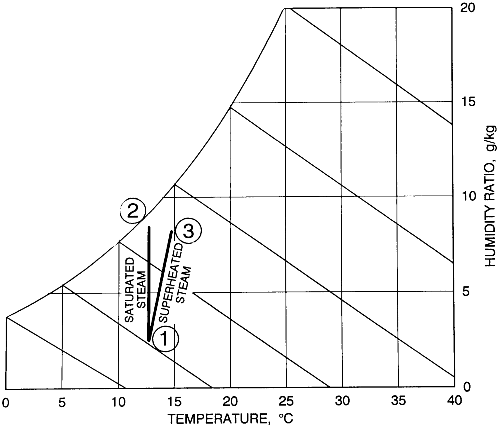
Steam, Hot-Water, and Electric Heating

Figure 1.9 Direct Expansion or Chilled Water Cooling and Dehumidification



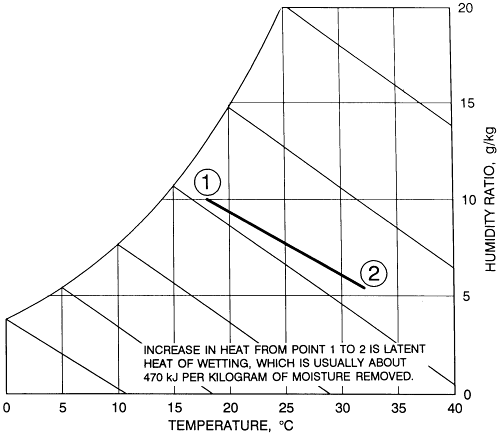
Humidification

Figure 1.10 Direct Expansion or Chilled Water Cooling and Dehumidification



Steam Humidifier

Figure 1.11 Direct Expansion or Chilled Water Cooling and Dehumidification



Chemical Dehumidifier

Figure 1.12 Direct Expansion or Chilled Water Cooling and Dehumidification

Table 1.12 Specific Enthalpy of Moist Air at Standard Atmospheric Pressure, 101.325 kPa
[2017F, Ch 1, Tbl 2, Abridged]

Temp., °C	Specific Enthalpy, kJ/kg_{da}	Temp., °C	Specific Enthalpy, kJ/kg_{da}
–60	–60.325	26	80.801
–55	–55.280	27	85.289
–50	–50.222	28	89.979
–45	–45.144	29	94.882
–40	–40.031	30	100.009
–35	–34.859	31	105.372
–30	–29.593	32	110.985
–25	–24.181	33	116.860
–20	–18.542	34	123.013
–10	–6.070	35	129.458
–8	–3.282	36	136.213
–6	–0.356	37	143.294
–4	2.728	38	150.720
–2	5.995	39	158.510
0	9.475	40	166.685
2	12.981	45	214.169
4	16.696	50	275.349
6	20.644	55	355.144
8	24.853	60	460.880
10	29.354	70	803.464
12	34.181	80	1541.765
14	39.371	90	3867.556
16	44.966		
18	51.011		
20	57.558		
21	61.037		
22	64.663		
23	68.444		
24	72.388		
25	76.503		

Table 1.13 Standard Atmospheric Data for Altitudes to 10 000 m
[2017F, Ch 1, Tbl 1]

Altitude, m	Temperature, °C	Pressure, kPa
–500	18.2	107.478
0	15.0	101.325
500	11.8	95.461
1000	8.5	89.875
1500	5.2	84.556
2000	2.0	79.495
2500	–1.2	74.682
3000	–4.5	70.108
4000	–11.0	61.640
5000	–17.5	54.020
6000	–24.0	47.181
7000	–30.5	41.061
8000	–37.0	35.600
9000	–43.5	30.742
10 000	–50	26.436

Source: Adapted from NASA (1976).

At sea level, standard temperature is 15°C; standard barometric pressure is 101.325 kPa. The temperature is assumed to decrease linearly with increasing altitude throughout the troposphere (lower atmosphere), and to be constant in the lower reaches of the stratosphere. The lower atmosphere is assumed to consist of dry air that behaves as a perfect gas. Gravity is also assumed constant at the standard value, 9.806 65 m/s^2.

The values in Table 1.13 may be calculated from Equation 1.6:

$$p = 101.325(1 - 2.25577 \times 10^{-5} Z)^{5.2559} \tag{1.6}$$

Space Air Diffusion

Room air diffusion methods can be classified as one of the following:

- **Fully mixed systems** produce little or no thermal stratification of air within the space. Overhead air distribution is an example of this type of system.
- **Fully (thermally) stratified systems** produce little or no mixing of air within the occupied space. Thermal displacement ventilation is an example of this type of system.
- **Partially mixed systems** provide some mixing within the occupied and/or process space while creating stratified conditions in the volume above. Most underfloor air distribution and task/ambient conditioning designs are examples of this type of system.

Air distribution systems, such as thermal displacement ventilation (TDV) and underfloor air distribution (UFAD), that deliver air in cooling mode at or near floor level and return air at or near ceiling level produce varying amounts of room air stratification. For floor-level supply, thermal plumes that develop over heat sources in the room play a major role in driving overall floor-to-ceiling air motion. The amount of stratification in the room is primarily determined by the balance between total room airflow and heat load. In practice, the actual temperature and concentration profile depends on the combined effects of various factors, but is largely driven by the characteristics of the room supply airflow and heat load configuration.

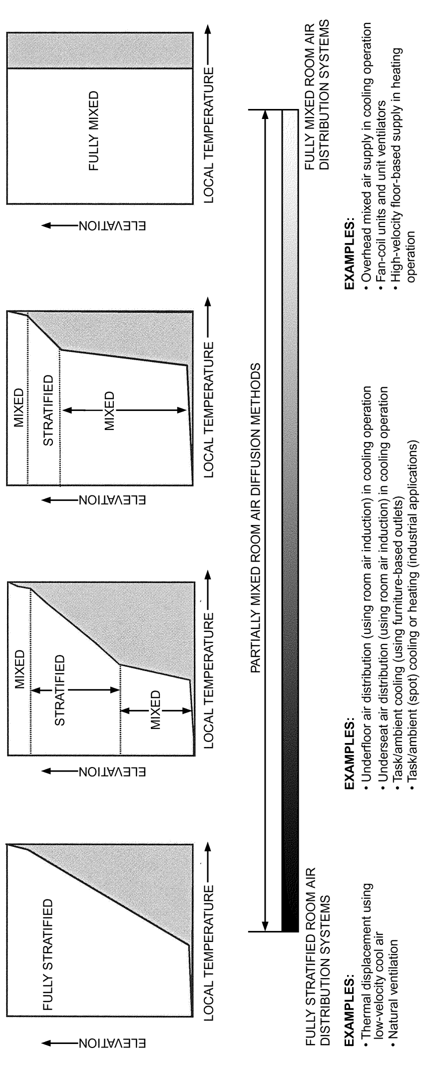


Figure 1.13 Classification of Air Diffusion Methods [2017F, Ch 20, Fig 1]

Principles of Jet Behavior

Air Jet Fundamentals

Air supplied to rooms through various types of outlets can be distributed by turbulent air jets (mixed and partially mixed systems) or in a low-velocity, unidirectional manner (stratified systems).

If an air jet is not obstructed or affected by walls, ceiling, or other surfaces, it is considered a **free jet**. When outlet area is small compared to the dimensions of the space normal to the jet, the jet may be considered free as long as

$$X \le 1.5\sqrt{A_R} \tag{1.7}$$

where

X	=	distance from face of outlet, m
A_R	=	cross-sectional area of confined space normal to jet, m^2

Characteristics of the air jet in a room might be influenced by reverse flows created by the same jet entraining ambient air. If the supply air temperature is equal to the ambient room air temperature, the air jet is called an **isothermal jet**. A jet with an initial temperature different from the ambient air temperature is called a **nonisothermal jet**. The air temperature differential between supplied and ambient room air generates thermal forces (buoyancy) in jets, affecting the jet's (1) trajectory, (2) location at which it attaches to and separates from the ceiling/floor, and (3) throw. The significance of these effects depends on the ratio between the thermal buoyancy of the air and jet momentum.

Jet Expansion Zones. The full length of an air jet, in terms of the maximum or centerline velocity and temperature differential at the cross section, can be divided into four zones:

- **Zone 1** is a short core zone extending from the outlet face, in which the maximum velocity and temperature of the airstream remains practically unchanged.
- **Zone 2** is a transition zone, with its length determined by the type of outlet, aspect ratio of the outlet, initial airflow turbulence, etc.
- **Zone 3** is a zone of jet degradation, where centerline air velocity and temperature decrease rapidly. Turbulent flow is fully established and may be 25 to 100 equivalent air outlet diameters (i.e., widths of slot air diffusers) long.
- **Zone 4** is of major engineering importance because, in most cases, the jet enters the occupied area in this zone. Distance to this zone and its length depend on the velocities and turbulence characteristics of ambient air. In a few diameters or widths, air velocity becomes less than 0.25 m/s.

Centerline Velocities in Zones 1 and 2. In zone 1, the ratio V_x/V_o is constant and ranges between 1.0 and 1.2, equal to the ratio of the center velocity of the jet at the start of expansion to the average velocity. The ratio V_x/V_o varies from approximately 1.0 for rounded entrance nozzles to about 1.2 for straight pipe discharges; it has much higher values for diverging discharge outlets.

Experimental evidence indicates that, in zone 2,

$$\frac{V_x}{V_o} = \sqrt{\frac{K_c H_o}{X}} \tag{1.8}$$

where

V_x	=	centerline velocity at distance X from outlet, m/s
V_o	=	$V_c / C_d R_{fa}$ = average initial velocity at discharge from open-ended duct or across contracted stream at vena contracta of orifice or multiple-opening outlet, m/s
V_c	=	nominal velocity of discharge based on core area, m/s
C_d	=	discharge coefficient (usually between 0.65 and 0.90)
R_{fa}	=	ratio of free area to gross (core) area
H_o	=	width of jet at outlet or at vena contracta, m
K_c	=	centerline velocity constant, depending on outlet type and discharge pattern (see Table 1.14)
X	≥	$(1/K_c H_o)^{1/2}$ = distance from outlet to measurement of centerline velocity V_x, m

Table 1.14 Generic Values for Centerline Velocity Constant K_c for Commercial Supply Outlets for Fully and Partially Mixed Systems, Except UFAD [2017F, Ch 20, Tbl 1]

Outlet Type	Discharge Pattern	A_o	K_c
High sidewall grilles	0° deflection[a]	Free	5.7
	Wide deflection	Free	4.2
High sidewall linear	Core less than 100 mm high[b]	Free	4.4
	Core more than 100 mm high	Free	5.0
Low sidewall	Up and on wall, no spread	Free	4.5
	Wide spread[b]	Free	3.0
Baseboard	Up and on wall, no spread	Core	4.0
	Wide spread	Core	2.0
Floor grille	No spread[b]	Free	4.7
	Wide spread	Free	1.6
Ceiling	360° horizontal[c]	Neck	1.1
	Four-way; little spread	Neck	3.8
Ceiling linear slot	Horizontal/vertical along surface[b]	Free	5.5
	Horizontal/vertical free jet	Free	3.9
	Free jet (air curtain units)	Free	6.0

[a]Free area is about 80% of core area.
[b]Free area is about 50% of core area.
[c]Cone free area is greater than duct area.

Centerline Velocity in Zone 3. In zone 3, centerline velocities of radial and axial isothermal jets can be determined accurately from Equation 1.9:

$$V_x = \frac{K_c V_o \sqrt{A_o}}{X} = \frac{K_c Q_o}{X\sqrt{A_o}} \tag{1.9}$$

where

K_c = centerline velocity constant
A_o = free area, core area, or neck area as shown in Table 1.15 (obtained from outlet manufacturer), m^2
A_c = measured gross (core) area of outlet, m^2
Q_o = discharge from outlet, cfm

The effective area, according to ASHRAE Standard 70, can be used in place of A_o in Equation 1.9 with the appropriate value of K_c.

Throw. Equation 1.9 can be transposed to determine the throw X of an outlet if the discharge volume and the centerline velocity are known:

$$X = \frac{K_c Q_o}{V_x\sqrt{A_o}} \tag{1.10}$$

Comparison of Free Jet to Attached Jet

Most manufacturers' throw data obtained in accordance with ASHRAE Standard 70 assume the discharge is attached to a surface. An attached jet induces air along the exposed side of the jet, whereas a free jet can induce air on all its surfaces. Because a free jet's induction rate is larger compared to that of an attached jet, a free jet's throw distance will be shorter. To calculate the throw distance X for a noncircular free jet from catalog data for an attached jet, the following estimate can be used.

$$X_{free} = X_{attached} \times 0.707 \tag{1.11}$$

Circular free jets generally have longer throws compared to noncircular jets.

Jets from ceiling diffusers initially tend to attach to the ceiling surface, because of the force exerted by the Coanda effect. However, cold air jets will detach from the ceiling if the air-stream's buoyancy forces are greater than the inertia of the moving air stream.

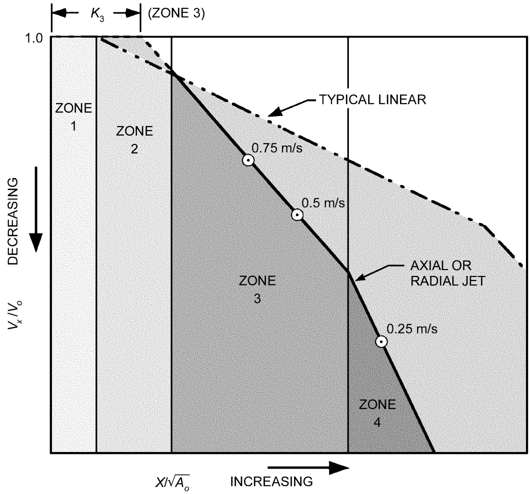
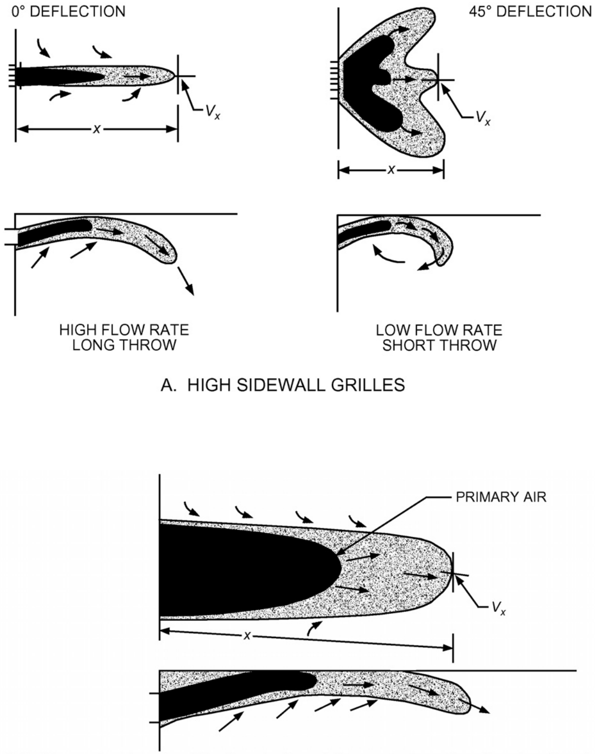


Figure 1.14 Chart for Determining Centerline Velocities of Axial and Radial Jets
[2017F, Ch 20, Fig 11]



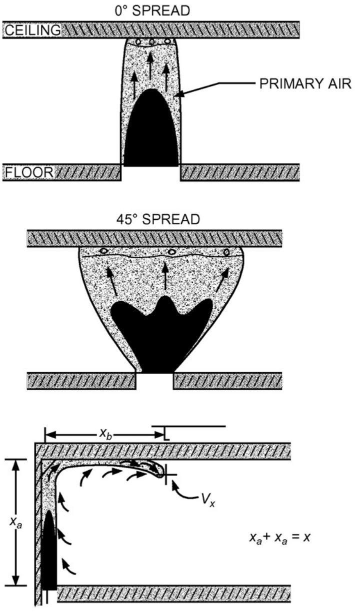
Note: Throw values based on 1.2 m long, isothermal active section. Correction multipliers for other lengths are as follows:

Active length, m	0.6	1.2	2.4	3
Throw correction	0.72	1	1.5	1.7

B. HIGH SIDEWALL LINEAR

Note: Airflow patterns shown with darker shading indicate primary air patterns for terminal velocities above 0.75 m/s.

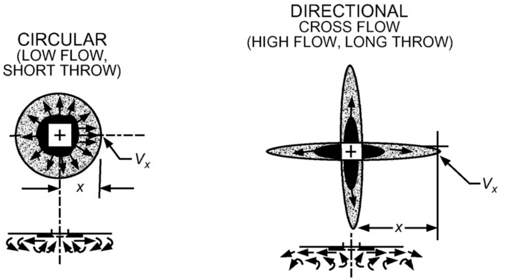
Figure 1.15 Airflow Patterns of Different Diffusers



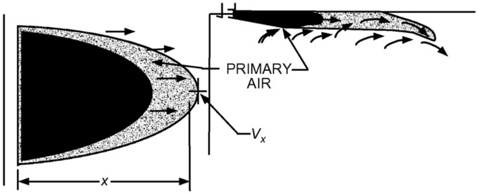
C. LOW SIDEWALL BASEBOARD OR FLOOR WITH VERTICAL DISCHARGE

Note: Airflow patterns shown with darker shading indicate primary air patterns for terminal velocities above 0.75 m/s.

Figure 1.15 Airflow Patterns of Different Diffusers *(Continued)*



D. CEILING DIFFUSERS



Note: Throw values based on 1.2 m long, isothermal active section. Correction multipliers for other lengths are as follows:

Active length, m	0.6	1.2	2.4	3
Throw correction	0.72	1	1.5	1.7

E. CEILING LINEAR

Note: Airflow patterns shown with darker shading indicate primary air patterns for terminal velocities above 0.75 m/s.

Figure 1.15 Airflow Patterns of Different Diffusers
(Continued)

System Design

Fully Mixed Air Distribution

In mixed air systems, high-velocity supply jets from air outlets maintain comfort by mixing room air with supply air. This air mixing, heat transfer, and resultant velocity reduction should occur outside the occupied zone. Occupant comfort is maintained not directly by motion of air from outlets, but from secondary air motion from mixing in the unoccupied zone. Comfort is maximized when uniform temperature distribution and room air velocities of less than 0.25m/s are maintained in the occupied zone.

Maintaining velocities less than 0.25m/s in the occupied zone is often overlooked by designers, but is critical to maintaining comfort. The outlet's selection, location, supply air volume, discharge velocity, and air temperature differential determine the resulting air motion in the occupied zone.

Principles of Operation

Mixed systems generally provide comfort by entraining room air into discharge jets located outside occupied zones, mixing supply and room air. Ideally, these systems generate low-velocity air motion (less than 0.25m/s) throughout the occupied zone to provide uniform temperature gradients and velocities. Proper selection of an air outlet is critical for proper air distribution; improper selection can result in room air stagnation, unacceptable temperature gradients, and unacceptable velocities in the occupied zone that may lead to occupant discomfort.

The location of a discharge jet relative to surrounding surfaces is important. Discharge jets attach to parallel surfaces, given sufficient velocity and proximity. When a jet is attached, the throw increases by about 40% over a jet discharged in an open area. This difference is important when selecting an air outlet. For detailed discussion of the surface effect on discharge jets, see Chapter 20 of the 2017 *ASHRAE Handbook—Fundamentals*.

Mixed air systems typically use either ceiling or sidewall outlets discharging air horizontally, or floor- or sill-mounted outlets discharging air vertically. They are the most common method of air distribution in North America.

Horizontal Discharge Cooling with Ceiling-Mounted Outlets

Ceiling-mounted outlets typically use the surface effect to transport supply air in the unoccupied zone. The supply air projects across the ceiling and, with sufficient velocity, can continue down wall surfaces and across floors. In this application, supply air should remain outside the occupied zone until it is adequately mixed and tempered with room air.

Overhead outlets may also be installed on exposed ducts, in which case the surface effect does not apply. Typically, if the outlet is mounted 300 mm or more below a ceiling surface, discharge air will not attach to the surface. The unattached supply air has a shorter throw and can project downward, resulting in high air velocities in the occupied zone. Some outlets are designed for use in exposed duct applications. Typical outlet performance data presented by manufacturers are for outlets with surface effect; consult manufacturers for information on exposed duct applications.

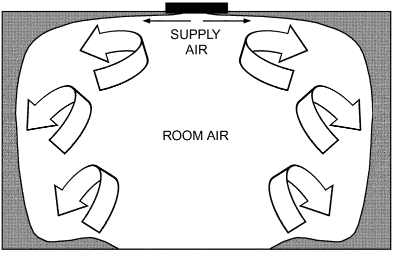


Figure 1.16 Air Supplied at Ceiling Induces Room Air into Supply Jet [2015A, Ch 57, Fig 3]

Vertical-Discharge Cooling or Heating with Ceiling-Mounted Outlets

Vertically projected outlets are typically selected for high-ceiling applications that require forcing supply air down to the occupied zone. It is important to keep cooling supply air velocity below 0.25 m/s in the occupied zone. For heating, supply air should reach the floor.

There are outlets specifically designed for vertical projection and it is important to review the manufacturer's performance data notes to understand how to apply catalog data. Throws for heating and cooling differ and also vary depending on the difference between supply and room air temperatures.

Cooling with Sidewall Outlets

Sidewall outlets are usually selected when access to the ceiling plenum is restricted. Sidewall outlets within 300 mm of a ceiling and set for horizontal or a slightly upward projection the sidewall outlet provide a discharge pattern that attaches to the ceiling and travels in the unoccupied zone. This pattern entrains air from the occupied zone to provide mixing.

In some applications, the outlet must be located 0.5 to 1.25 m below the ceiling. When set for horizontal projection, the discharge at some distance from the outlet may drop into the occupied zone. Most devices used for sidewall application can be adjusted to project the air pattern upwards toward the ceiling. This allows the discharge air to attach to the ceiling, increasing throw distance and minimizing drop. This application provides occupant comfort by inducing air from the occupied zone into the supply air.

Some outlets may be more than 1.25 m below the ceiling (e.g., in high-ceiling applications, the outlet may be located closer to the occupied zone to minimize the volume of the conditioned space). Most devices used for sidewall applications can be adjusted to project the air pattern upward or downward, which allows the device's throw distance to be adjusted to maximize performance.

When selecting sidewall outlets, it is important to understand the manufacturer's data. Most manufacturers offer data for outlets tested with surface effect, so they only apply if the device is set to direct supply air toward the ceiling. When the device is 1.25 m or more below a ceiling, or supply air is directed horizontally or downward, the actual throw distance of the device is typically shorter. Many sidewall outlets can be adjusted to change the spread of supply air, which can significantly change throw distance. Manufacturers usually publish throw distances based on specific spread angles.

Cooling with Floor-Mounted Air Outlets

Although not typically selected for nonresidential buildings, floor-mounted outlets can be used for mixed system cooling applications. In this configuration, room air from the occupied zone is induced into the supply air, providing mixing. When cooling, the device should be selected to discharge vertically along windows, walls, or other vertical surfaces. Typical nonresidential applications include lobbies, long corridors, and houses of worship.

It is important to select a device that is specially designed for floor applications. It must be able to withstand both the required dynamic and static structural loads (e.g., people walking on them, loaded carts rolling across them). Also, many manufacturers offer devices designed to reduce the possibility of objects falling into the device. It is strongly recommended that obstructions are not located above these in-floor air terminals, to avoid restricting their air jets.

Long floor-mounted grilles generally have both functioning and nonfunctioning segments. When selecting air outlets for floor mounting, it is important to note that the throw distance and sound generated depend on the length of the active section. Most manufacturers' catalog data include correction factors for length's effects on both throw and sound. These corrections can be significant and should be evaluated. Understanding manufacturers' performance data and corresponding notes is imperative.

Cooling with Sill-Mounted Air Outlets

Sill-mounted air outlets are commonly used in applications that include unit ventilators and fan coil units. The outlet should be selected to discharge vertically along windows, walls, or other vertical surfaces, and project supply air above the occupied zone.

As with floor-mounted grilles, when selecting and locating sill grilles, consider selecting devices designed to reduce the nuisance of objects falling inside them. It is also recommended that sills be designed to prevent them from being used as shelves.

Heating and Cooling with Perimeter Ceiling-Mounted Outlets

When air outlets are used at the perimeter with vertical projection for heating and/or cooling, they should be located near the perimeter surface, and selected so that the published 0.75 m/s isothermal throw extends at least halfway down the surface or 1.5 m above the floor, whichever is lower. In this manner, during heating, warm air mixes with the cool downdraft on the perimeter surface, to reduce or even eliminate drafts in the occupied space.

If a ceiling-mounted air outlet is located away from the perimeter wall, in cooling mode, the high-velocity cool air reduces or overcomes the thermal updrafts on the perimeter surface. To accomplish this, the outlet should be selected for horizontal discharge toward the wall. Outlet selection should be such that isothermal throw to the terminal velocity of 0.75 m/s should include the distance from the outlet to the perimeter surface. For heating, the supply air temperature should not exceed 8.5°C above the room air temperature.

Space Temperature Gradients and Airflow Rates

A fully mixed system creates homogeneous thermal conditions throughout the space. As such, thermal gradients should not be expected to exist in the occupied zone. Improper selection, sizing, or placement may prevent full mixing and can result in stagnant areas, or having high-velocity air entering the occupied zone.

Supply airflow requirements to satisfy space sensible heat gains or losses are inversely proportional to the temperature difference between supply and return air. Equation 1.12 can be used to calculate space airflow requirements (at standard conditions):

$$Q = \frac{q_s}{1.2(t_r - t_s)} \tag{1.12}$$

where

Q	=	required supply airflow rate to meet sensible load, L/s
q_s	=	net sensible heat gain in the space, W
t_r	=	return or exhaust air temperature, °C
t_s	=	supply air temperature, °C

For fully mixed systems with conventional ceiling heights, the return (or exhaust) and room air temperatures are the same; for example, a room with a set-point temperature of 24°C has, on average, a 24°C return or exhaust air temperature.

The object of air diffusion in warm-air heating, ventilating, and air-conditioning systems is to create the proper combination of temperature, humidity, and air motion in the occupied zone of the conditioned room—from the floor to 2 m above floor level.

Discomfort can arise due to any of the following: excessive air motion (draft), excessive room air temperature variations (horizontal, vertical, or both), failure to deliver or distribute air according to the load requirements at different locations, overly rapid fluctuation of room temperature.

Air Diffusion Performance Index (ADPI)

ADPI is the percentage of locations where measurements are taken that meet these specifications for effective draft temperature and air velocity. If the ADPI is maximum (approaching 100%), the most desirable conditions are achieved. ADPI should be used only for cooling mode in sedentary occupancies. Where air does not strike a wall but collides with air from a neighboring diffuser, *L* is one-half the distance between the diffusers plus the distance the mixed air drops to the occupied zone.

Table 1.15 Characteristic Room Length for Several Diffusers
[2015A, Ch 57, Tbl 5]

Diffuser Type	Characteristic Length L
High sidewall grille	Distance to wall perpendicular to jet
Circular ceiling pattern diffuser	Distance to closest wall or intersecting air jet
Sill grille	Length of room in direction of jet flow
Ceiling slot diffuser	Distance to wall or midplane between outlets
Light troffer diffusers	Distance to midplane between outlets plus distance from ceiling to top of occupied zone
Perferated, louvered ceiling diffusers	Distance to wall or midplane between outlets

Table 1.16 Air Diffusion Performance Index (ADPI) Selection Guide
[2015A, Ch 57, Tbl 6]

Terminal Device	Room Load, W/m^2	$X_{0.25}/L$ for Maximum ADPI	Maximum ADPI	For ADPI Greater than	Range of $X_{0.25}/L$
High sidewall grilles	250	1.8	68	—	—
	190	1.8	72	70	1.5 to 2.2
	125	1.6	78	70	1.2 to 2.3
	65	1.5	85	80	1.0 to 1.9
	30	1.4	90	80	0.7 to 2.1
Circular ceiling diffusers	250	0.8	76	70	0.7 to 1.3
	190	0.8	83	80	0.7 to 1.2
	125	0.8	88	80	0.5 to 1.5
	65	0.8	93	80	0.4 to 1.7
	30	0.8	99	80	0.4 to 1.7
Sill grille, straight vanes	250	1.7	61	60	1.5 to 1.7
	190	1.7	72	70	1.4 to 1.7
	125	1.3	86	80	1.2 to 1.8
	65	0.9	95	90	0.8 to 1.3
Sill grille, spread vanes	250	0.7	94	90	0.6 to 1.5
	190	0.7	94	80	0.6 to 1.7
	125	0.7	94	—	—
	65	0.7	94	—	—
Ceiling slot diffusers (for $T_{0.5}/L$)	250	0.3	85	80	0.3 to 0.7
	190	0.3	88	80	0.3 to 0.8
	125	0.3	91	80	0.3 to 1.1
	65	0.3	92	80	0.3 to 1.5
Light troffer diffusers	190	2.5	86	80	<3.8
	125	1.0	92	90	<3.0
	65	1.0	95	90	<4.5
Perforated, louvered diffusers	35 to 160	2.0	96	90	1.4 to 2.7
	35 to 160	2.0	96	80	1.0 to 3.4

Fully Stratified Air Distribution

Systems that discharge cool air at low sidewall or floor locations with very little entrainment of (and thus mixing with) room air create (vertical) thermal stratification throughout the space. These **displacement ventilation** systems have been popular in northern Europe for some time. Floor-based outlets in underfloor applications may also be used to provide fully stratified air distribution.

Principles of Operation

Thermal displacement ventilation (TDV) systems (see Figure 1.17) use very low discharge velocities, typically 0.25 to 0.35 m/s, to deliver cool supply air to the space. The discharge temperature of the supply air is generally above 16°C, although lower temperatures may be used in industrial applications, exercise or sports facilities, and transient areas. The cool air is negatively buoyant compared to ambient air and drops to the floor after discharge. It then spreads across the lower level of the space.

As convective heat sources (see Figure 1.17) in the space transfer heat to the cooler air around them, natural convection currents form and rise along the heat transfer boundary. Without significant room air movement, these currents rise to form a convective heat plume around and above the heat source. As the plume rises, it expands by entraining surrounding air. Its growth and ascent are proportional to the heat source's size and intensity and temperature of ambient air above it. Ambient air from below and around the heat source fills the void created by the rising plume. If the heat source is near the floor (e.g., an occupant), the plume entrains cool, conditioned air from the floor level, which is drawn to the respiration level, and serves as the source of inhaled air. Exhaled air rises with the escaping heat plume, because it is warmer and more humid than the ambient air. Convective heat from sources located above the occupied zone has little effect on occupied-zone air temperature.

At a certain height, where plume temperature equals ambient temperature, the plume disintegrates and spills horizontally. Two distinct zones are thus formed in the room: a lower occupied zone with little or no recirculation flow (close to displacement flow), and an upper zone with recirculation flow. The boundary between these two zones is called **shift zone**. The shift zone height is calculated as the height above the floor where the total amount of air carried in convective plumes above heat sources equals the supply airflow distributed through displacement diffusers. Actual and simplified representations of the temperature gradient in the space are shown in Figure 1.18.

Outlet Characteristics

Displacement outlets are designed for average face velocities between 0.25 to 0.35 m/s, and are typically in a low sidewall or floor location. Return or exhaust air intakes should always be located above the occupied zone for human thermal comfort applications.

Displacement outlets are available in a number of configurations and sizes. Some models are designed to fit in corners or along sidewalls, or stand freely as columns. It is important to consider the degree of flow equalization the outlet achieves, because use of the entire outlet surface for air discharge is paramount to minimizing clear zones and maintaining acceptable temperatures at the lower levels of the space.

Stationary occupants should not be subjected to discharge velocities exceeding about 0.2 m/s because air at the ankle level within this velocity envelope tends to be quite cool. As such, most outlet manufacturers define a **clear zone** in which location of stationary, low-activity occupants is strongly discouraged, but transient occupancy, such as in corridors or aisles, is possible. Occupants with high activity levels may also find the clear zone acceptable.

Unlike mixed systems, outlets in thermal displacement systems discharge air at very low velocities, resulting in very little mixing. As such, design of these systems primarily involves determining a supply airflow rate to manage the thermal gradients in the space in accordance with ASHRAE comfort guidelines. ASHRAE Standard 55 recommends that the vertical temperature difference between the ankle and head levels of space occupants be limited to no more than 3 K to maintain a high degree (>95%) of occupant satisfaction.

Application Considerations

Displacement ventilation is a cooling-only method of room air distribution. For heating, a separate system is generally recommended. Displacement ventilation can be used successfully in

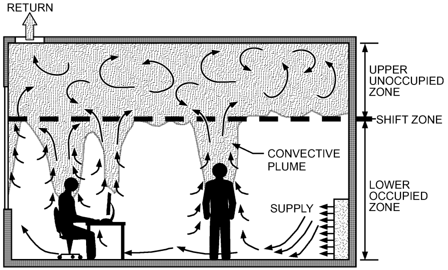


Figure 1.17 Displacement Ventilation System Characteristics [2015A, Ch 57, Fig 4]

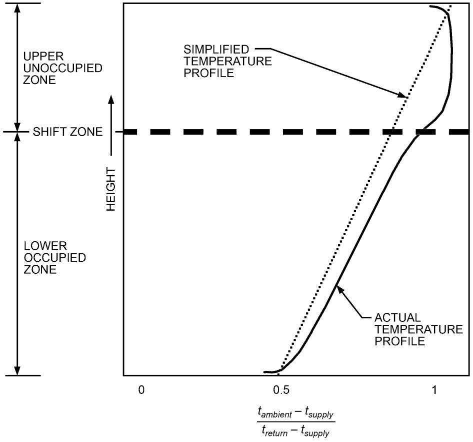


Figure 1.18 Temperature Profile of Displacement Ventilation [2015A, Ch 57, Fig 5]

combination with radiators and convectors installed at the exterior walls to offset space heat losses. Radiant heating panels and heated floors also can also be used with displacement ventilation. To maintain displacement ventilation, outlets should supply ventilation air about 2 K lower than the desired room temperature.

Thermal displacement ventilation systems can be either constant or variable air volume. A thermostat in a representative location in the space or return plenum should determine the delivered air volume or temperature. If the time-averaged requirements of ASHRAE Standard 62.1-2004 are met, intermittent on/off airflow control can be used.

Avoid using thermal displacement and mixed air systems in the same space, because mixing destroys the natural stratification that drives the thermal displacement ventilation system. Thermal displacement systems can be complemented by hydronic systems such as chilled floors. Use caution when combining chilled ceilings, beams, or panels with fully stratified systems, because cold surfaces in the upper zone of the space may recirculate contaminants stratified in the upper zone back into the occupied zone.

Partially Mixed Air Distribution

A partially mixed system's characteristics fall between a fully mixed system and a fully stratified system. It includes both a high-velocity mixed air zone and a low-velocity stratified zone where room air motion is caused by thermal forces. For example, floor-based outlets, when operating in a cooling mode with relatively high discharge velocities (>0.75 m/s), create mixing, thus affecting the amount of stratification in the lower portions of the room. In the upper portions of the room, away from the influence of floor outlets, room air often remains thermally stratified in much the same way as displacement ventilation systems.

Principles of Operation

Supply air is discharged, usually vertically, at relatively high velocities and entrains room air in a similar fashion to outlets used in mixed air systems. This entrainment, as shown in Figure 1.19 reduces the temperature and velocity differentials between supply and ambient room air. This discharge results in a vertical plume that rises until its velocity is reduced to about 0.25 m/s. At this point, its kinetic energy is insufficient to entrain much more room air, so mixing stops. Because air in the plume is still cooler than the surrounding air, the supply air spreads horizontally across the space, where it is entrained by rising thermal plumes generated by nearby heat sources.

Research and experience have shown that the amount of room air stratification varies depending on design, commissioning, and operation. Control of stratification includes the following considerations:

- By reducing airflow and mixing in the occupied zone, fan energy can be reduced and stratification can be increased, approaching a reasonable target at 1.5 to 2.5 K temperature difference from head to ankle height, which satisfies ASHRAE Standard 55-2010.
- By increasing airflow and mixing in the occupied zone, excessive stratification can be avoided, thereby improving thermal comfort.

Figure 1.19 shows one example of the resulting room air distribution in which the room air is mixed in the **lower mixed zone**, which is bounded by the floor and the elevation (**throw height**) at which the 0.25 m/s terminal velocity occurs. At this elevation, stratification begins to occur and a linear temperature gradient, similar to that found in thermal displacement systems, forms and extends through the **stratified zone**. As with thermal displacement ventilation, convective heat plumes from space heat sources draw conditioned air from the lower (mixed) level through the stratified zone and to the overhead return location. A third zone, referred to as the **upper mixed zone**, may exist where the volume of rising heat plumes terminate. Although velocities in this area are quite low, the air tends to be mixed.

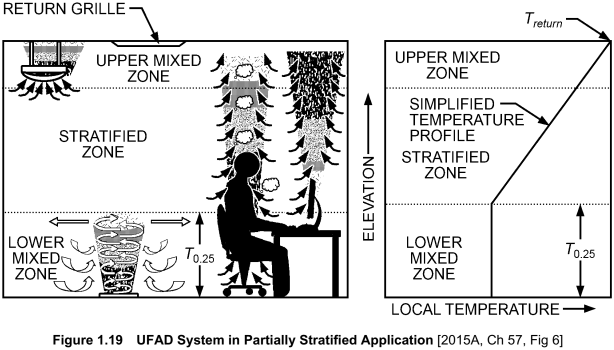


Figure 1.19 UFAD System in Partially Stratified Application [2015A, Ch 57, Fig 6]

Outlet Characteristics

One outlet type is a swirl diffuser with a high-induction core, which induces large amounts of room air to quickly reduce supply to ambient air velocity and temperature differentials. Supply air is injected into the room as a swirling vertical plume close to the outlet. Properly selected, these outlets produce a limited vertical projection of the supply air plume, restricting mixing to the lower portions of the space. Most of these outlets allow occupants to adjust the outlet airflow rate easily. Other versions incorporate automatically controlled dampers that are repositioned by a signal from the space thermostat and/or central control system.

Another category includes more conventional floor grilles designed for directional discharge of supplied airflow. These grilles may be either linear or modular in design, and may allow occupants to adjust the discharge air pattern by repositioning the core of the outlet. Most floor grilles include an integral actuated damper, or other means, that automatically throttles the volume of air in response to the zone conditioning requirements.

Room air induction allows UFAD diffusers to comfortably deliver supply air a few degrees cooler than possible with outlets used for thermal displacement ventilation outlets. The observance of clear, or adjacent, zones above and around the diffusers, where stationary occupants should not reside, is recommended. Outlet manufacturers typically identify such restrictive areas in their product literature.

As for thermal displacement systems, design involves determining a supply airflow rate that limits thermal gradients in the occupied zone in accordance with ASHRAE Standard 55 guidelines. ASHRAE Standard 55 recommends that the vertical temperature difference between the ankle and head level of space occupants be limited to no more than 3 K if a high degree (>95%) of occupant comfort is to be maintained.

Application Considerations

Some considerations include the following:

- Supply temperatures in the access floor cavity should be kept at 16°C or above, to minimize the risk of condensation and subsequent mold growth.
- Most UFAD outlets can be adjusted automatically by a space thermostat or other control system, or manually by the occupant. In the latter case, outlets should be located within the workstation they serve.
- Use of manually adjusted outlets should be restricted to open office areas where cooling loads do not tend to vary considerably or frequently. Perimeter areas and conference rooms require automatic control of supply air temperatures and/or flow rates because their thermal loads are highly transient.
- Heat transfer to and from the floor slab affects discharge air temperature and should be considered when calculating space airflow requirements. Floor plenums should be well sealed to minimize air leakage, and exterior walls should be well insulated and have good vapor retarders. Night and holiday temperature setbacks should likely be avoided, or at least reduced, to minimize plenum condensation and thermal mass effect problems. With air-side economizers, using enthalpy control rather than dry-bulb control can help reduce hours of admitting high moisture-content air, thus also reducing the potential for condensation in the floor plenums.
- Avoid using stratified and mixed air systems in the same space, because mixing destroys the natural stratification that drives the stratified system.
- Return static pressure drop should be relatively equal throughout the spaces being served by a common UFAD plenum. This reduces the chance of unequal pressurization in the UFAD plenum.

Return Air Inlets

The success of a mixed air distribution system depends primarily on supply diffuser location. Return grille location is far less critical than with outlets. In fact, the return air intake affects room air motion only immediately around the grille. Measurements of velocity near a return air grille show a rapid decrease in magnitude as the measuring device is moved away from the grille face. Table 1.17 shows recommended maximum return air grille velocities as a function of grille location. Every enclosed space should have return/transfer inlets of adequate size per this table.

For stratified and partially mixed air distribution systems, there are advantageous locations for return air inlets. For example, an intake can be located to return the warmest air in cooling season.

If the outlet is selected to provide adequate throw and directed away from returns or exhausts, supply short-circuiting is normally not a problem. The success of this practice is confirmed by the availability and use of combination supply and return diffusers.

Table 1.17 Recommended Return Inlet Face Velocities
[2015A, Ch 57, Tbl 4]

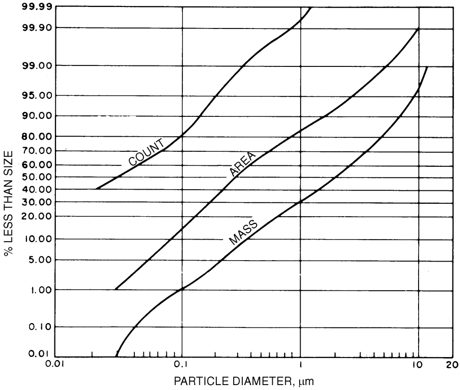
Inlet Location	Velocity Across Gross Area, m/s
Above occupied zone	>4
In occupied zone, not near seats	3 to 4
In occupied zone, near seats	2 to 3
Door or wall louvers	1 to 1.5
Through undercut area of doors	1 to 1.5

2. AIR CONTAMINANTS AND CONTROL

Table 2.1 National Ambient Air Quality Standards for the United States
[2017F, Ch 11, Tbl 12]

Contaminant	Primary or Secondary Standard	Averaging Time	Level	Details
Carbon monoxide	Primary	1 h 8 h	35 ppm 9 ppm	Not to be exceeded more than once per year
Nitrogen dioxide	Primary	1 h	100 ppb	98th percentile, averaged over 3 years
	Primary/ secondary	1 yr	53 ppb	Annual mean
Ozone	Primary/ secondary	8 h	75 ppb	Annual fourth-highest daily maximum 8 h concentration, averaged over 3 years
Sulfur dioxide	Primary	1 h	75 ppb	99th percentile of 1 h daily maximum concentrations, averaged over 3 years
	Secondary	3 h	500 ppb	Not to be exceeded more than once per year
Particulate, $PM_{2.5}$[a]	Primary/ secondary	24 h	35 μg/m^3	98th percentile, averaged over 3 years
		1 yr	15 μg/m^3	Annual mean, averaged over 3 years
Particulate, PM_{10}[b]	Primary/ secondary	24 h	150 μg/m^3	Not to be exceeded more than once per year on average over 3 years
Lead (Pb) in particles	Primary/ secondary	3 mo	0.15 μg/m^3	Not to be exceeded

[a] $PM_{2.5}$ = particulates below 2.5 μm diameter.
[b] PM_{10} = particulates below 10 μm diameter.
ppb = parts per 10^9
Source: *National Ambient Air Quality Standards* (NAAQS), U.S. Environmental Protection Agency, Washington, DC, 2015.



Count curve: Based on measurements by electron microscope.
Area curve: Calculated.
Mass curve: Solid section based on measurements by sedimentation.

Figure 2.1 Particle Size Distribution of Atmospheric Dust

Air Contaminants and Control

Electronic Air Cleaners

Electronic air cleaners use electrostatic precipitation to remove and collect particulate contaminants such as dust, smoke, and pollen. Wires with a positive direct current potential of between 6 and 25 kV DC are suspended equidistant between grounded plates, creating an ionizing field for charging particles.

The collecting plate section consists of parallel plates with a positive voltage of 4 to 10 kV (dc) applied to alternate plates. Plates that are not charged are at ground potential. As particles pass into this section, they are forced to the plates by the electric field on the charges they carry, and thus are removed from the airstream and collected by the plates.

Electronic air cleaners typically operate from a 120- or 240-V AC single-phase electrical service. Power consumption ranges from 10 to 20 watts per 1000 L/s.

This type of air filter can remove and collect airborne contaminants with average efficiencies of up to 98% at low airflow velocities (0.75 to 1.75 m/s) when tested per ASHRAE Standard 52.1. Efficiency decreases (1) as the collecting plates become loaded with particulates, (2) with higher velocities, or (3) with nonuniform velocity.

As with most air filtration devices, the duct approaches to and from the air cleaner housing should be arranged so that the airflow is distributed uniformly over the face area. Panel prefilters should also be used to help distribute the airflow and to trap large particles that might short out or cause excessive arcing within the high-voltage section.

Bioaerosols

Bioaerosols, particulates of biological origin, are of concern in indoor air due to their association with allergies and asthma and their ability to cause disease.

Airborne viral and bacterial aerosols are generally transmitted by droplet nuclei, averaging about 3 μm in diameter. Fungal spores range between 2 μm and 5 μm. Fifty to seventy percent dust spot efficiency filters can remove most microbial agents 1 μm to 2 μm in diameter. Sixty percent dust spot efficiency filters can remove 85% or more of 2.5 μm particles; while 85% filters can remove about 96%.

Filter Installation

Efficiency is sharply reduced if air leaks through poorly designed or installed frames. Install filters with face area at right angles to air flow whenever possible. Install high-efficiency filters as close as possible to the room to minimize pickup of particles between filter and outlet. Provide at least 500 mm access in front of or behind filters, or both.

ASHRAE Air Filtration Standards

ASHRAE Standard 52.1 (withdrawn in 2009) contained a test procedure for measuring the weight of a synthetic dust captured by a filter (arrestance). This gives a standard for comparing ability of fibers to remove coarse particles. ASHRAE Standard 52.2 contains the test procedure for comparing filter removal efficiency by particle size. For more efficient filters, arrestance is essentially 100% efficient, and their efficiency in removing smaller particles is tested. The dust spot efficiency of Standard 52.1 is replaced by the Standard 52.2 tests and classification.

Table 2.2 Filter Minimum Efficiency Reporting Value (MERV) Parameters

Standard 52.2 Minimum Efficiency Reporting Value (MERV)	Composite Average Particle Size Efficiency, % in Size Range, μm			Average Arrestance,%, by Standard 52.1 Method	Minimum Final Resistance	
	Range 1 0.30–1.0	Range 2 1.0–3.0	Range 3 3.0–10.0		Pa	in. of water
1	n/a	n/a	$E_3 < 20$	$A_{avg} < 65$	75	0.3
2	n/a	n/a	$E_3 < 20$	$65 \leq A_{avg} < 70$	75	0.3
3	n/a	n/a	$E_3 < 20$	$70 \leq A_{avg} < 75$	75	0.3
4	n/a	n/a	$E_3 < 20$	$75 \leq A_{avg}$	75	0.3
5	n/a	n/a	$20 \leq E_3 < 35$	n/a	150	0.6
6	n/a	n/a	$35 \leq E_3 < 50$	n/a	150	0.6
7	n/a	n/a	$50 \leq E_3 < 70$	n/a	150	0.6
8	n/a	n/a	$70 \leq E_3$	n/a	150	0.6
9	n/a	$E_2 < 50$	$85 \leq E_3$	n/a	250	1.0
10	n/a	$50 \leq E_2 < 65$	$85 \leq E_3$	n/a	250	1.0
11	n/a	$65 \leq E_2 < 80$	$85 \leq E_3$	n/a	250	1.0
12	n/a	$80 \leq E_2$	$90 \leq E_3$	n/a	250	1.0
13	$E_1 < 75$	$90 \leq E_2$	$90 \leq E_3$	n/a	350	1.4
14	$75 \leq E_1 < 85$	$90 \leq E_2$	$90 \leq E_3$	n/a	350	1.4
15	$85 \leq E_1 < 95$	$90 \leq E_2$	$90 \leq E_3$	n/a	350	1.4
16	$95 \leq E_1$	$95 \leq E_2$	$95 \leq E_3$	n/a	350	1.4

Table 2.3 Filter Application Guidelines [2016S, Ch 29, Tbl 3]

	Standard 52.2 MERV	Intended Standard 52.1 Value	Arrestance Value	Example Range of Contaminants Controlled	Example Applications	Sample Air Cleaner Type(s)
HEPA Filters	N/A	N/A	N/A	0.12 to 0.5 μm particles: virus (unattached), carbon dust, sea salt, radon progeny, combustion smoke	Cleanroom, pharmaceutical manufacturing and exhaust, radioactive material handling and exhaust, orthopedic and organ transplant surgery, carcinogenic materials, welding fumes	SULPA >99.999% 0.1 to 0.2 μm IEST type F (ceiling panel) ULPA >99.999% 0.3 μm IEST type D (ceiling panel) HEPA > 99.99% 0.3 μm IEST type C (ceiling or up to 300 mm deep) HEPA > 99.97% 0.3 μm IEST type A (box style 150 to 300 mm deep)
E-1 Range	MERV 16 MERV 15 MERV 14	Intended to replace 70 to 98% dust-spot efficiency filters	N/A	0.3 to 1.0 μm size range: bacteria, smoke (ETS), paint pigments, face powder, some virus, droplet nuclei, insecticide dusts, soldering fumes	Day surgery, general surgery, hospital general ventilation, turbo equipment, compressors, welding/soldering air cleaners, prefilters to HEPAs, LEED for existing (EB) and new (NC) commercial buildings, smoking lounges	Box-style wet-laid or lofted fiberglass, box-style synthetic media, minipleated synthetic or fiberglass paper, depths from 100 to 300 mm, Pocket filters of fiberglass or synthetic media 300 to 900 mm.
E-2 Range	MERV 12 MERV 11 MERV 10 MERV 9	Intended to replace 50 to 80% dust-spot efficiency filters	N/A	1.0 to 3.0 μm size range: milled flour, lead dust, combustion soot, *Legionella*, coal dust, some bacteria, process grinding dust	Food processing facilities, air separation plants, commercial buildings, better residential, industrial air cleaning, prefiltration to higher-efficiency filters, schools, gymnasiums	Box-style wet-laid or lofted fiberglass, box-style synthetic media, minipleated synthetic or fiberglass paper, depths from 50 to 300 mm. Pocket filters either rigid or flexible in synthetic or fiberglass, depths from 300 to 900 mm.
E-3 Range	MERV 8 MERV 7 MERV 6 MERV 5	Intended to replace 20 to 60% dust-spot efficiency filters	N/A	3.0 to 10 μm size range: pollens, earth-origin dust, mold spores, cement dust, powdered milk, snuff, hair spray mist	General HVAC filtration, industrial equipment filtration, commercial property, schools, prefilter to high-efficiency filters, paint booth intakes, electrical/phone equipment protection	Wide range of pleated media, ring panels, cubes, pockets in synthetic or fiberglass, disposable panels, depths from 25 to 600 mm.
	MERV 4 MERV 3 MERV 2 MERV 1	<20% <20% <20% <20%	>70% >70% >65% <65%	Arrestance method	Protection from blowing large particle dirt and debris, industrial environment ventilation air	Inertial separators

Note: MERV also includes test airflow rate, but it is not shown here because it is of no significance for the purposes of this table.
N/A = not applicable.

Table 2.4 Sources and Indoor and Outdoor Concentrations of Selected Indoor Contaminants [2017F, Ch 11, Tbl 13]

Contaminant	Sources of Indoor Contaminants	Typical Indoor Concentration	Typical Outdoor Concentration	Locations
Carbon monoxide	Combustion equipment, engines, faulty heating systems	0.5 to 5 ppm[a] (without gas stoves) 5 to 15 ppm[a] (with gas stoves)	2 ppm[a]	Indoor ice rinks, homes, cars, vehicle repair shops, parking garages
$PM_{2.5}$	Stoves, fireplaces, cigarettes, condensation of volatiles, aerosol sprays, cooking	7 to 10 μg/m³[a]	<10 μg/m³[a]	Homes, offices, cars, public facilities, bars, restaurants
PM_{10}	Combustion, heating system, cooking	40 to 60 μg/m³[a]	60 μg/m³[a]	Homes, offices, transportation, restaurants
Organic vapors	Combustion, solvents, resin products, pesticides, aerosol sprays, cleaning products, building materials, paints	Different for each VOC[c] (2 to 5 times outdoor levels)	See 2017F, Ch 11, Tbl 11	Homes, restaurants, public facilities, offices, hospitals
Nitrogen dioxide	Combustion, gas stoves, water heaters, gas-fired dryers, cigarettes, engines	<8 ppb[a] (without combustion appliances) >15 ppb with combustion appliances)	15 ppb[a]	Homes, indoor ice rinks
Nitric oxide	Combustion, gas stoves, water heaters, gas-fired dryers, cigarettes, engines	—	Various	Homes, any building with combustion source
Sulfur dioxide	Heating system	20 μg/m³[b]	<20 μg/m³[b] 3 ppb[a]	Mechanical/furnace rooms
Formaldehyde	Insulation, product binders, pressed wood products, carpets	0.1 to 0.3 ppm[a]	NA	Homes, schools, offices
Radon and progeny	Building materials, groundwater, soil	1.3 pCi/L[a]	4 pCi/L[a]	Homes, schools
Carbon dioxide	Combustion appliances, humans, pets	600 to 1000 ppm[c]	300 to 500 ppm[c]	
Biological contaminants	Humans, pets, rodents, insects, plants, fungi, humidifiers, air conditioners	NA	NA (lower than indoor levels)	Homes, hospitals, schools, offices, public facilities
Ozone	Electric arcing, electronic air cleaners, copiers, printers	42 ppb[d]	70 ppb[a]	Airplanes, offices, homes

Sources:
[a]EPA (2011)
[b]NRC (1981)
[c]Seppänen et al. (1999) and ASHRAE Standard 62.1, Appendix C
[d]Weschler (2000)

NA = not applicable
ppb = parts per 10^9

Table 2.5 Media Selection by Contaminant [2015A, Ch546, Tbl 7]

Gaseous Contaminant	PIA	AC	AIC	BIC	Gaseous Contaminant	PIA	AC	AIC	BIC	Gaseous Contaminant	PIA	AC	AIC	BIC
Acetaldehyde	1	2			Dichlorofloromethane		1			Methyl formate	2	1		
Acetic acid (!)	1	2		2,1	R-114 (see note)		1			Methyl isobutyl ketone	2	1		
Acetic anhydride (!)	1,2	1		2	Diethylamine	2	1			Methyl sulfide	1			
Acetone (!)	1	2			Dimethylamine		1	2		Methyl vinyl ketone	2	1		
Acetylene	1				Dioctyl phthalate		1			Naphtha		1		
Acrolein	1	2			Dioxane	1	2			Naphthalene		1		
Acrylic acid (!)	1	1		2	Ethanol	1	2			Nicotine	1	2		
Allyl sulfide	1	2			Ethyl acetate	2	1			Nitric acid				1
Ammonia (NH_3)			1		Ethyl chloride (!)	1,2	2,1			Nitric oxide (NO)	1			2
Aniline	2	1			Ethylene (C_2H_4)	1				Nitrobenzene		1		
Arsine	1				Ethylene oxide	1	2			Nitrogen dioxide	1			2
Benzene		1			Ethyl ether	2	1			Nitromethane	1			
Borane (!)	1	2,2			Ethyl mercaptan (!)	1,1	2		2	Nitrous oxide				1
Bromine		1			Formaldehyde	1				Octane (!)	2	1,1		
1,3 Butadiene	1	2			Gasoline	1				Ozone (O_3) (!)	2	1,1		
Butane		1			General halocarbons		1			Perchloroethylene	2	1		
2-Butanone	1	2			General hydrocarbons	2	1			Peroxy acetyl nitrate (PAN)		1		
2-Butoxyethanol	2	1			General VOC	2	1			Phenol	2	1		
Butyl acetate (!)	1,2	2,1			Heptane		1			Phosgene	2	1		
Butyl alcohol	2	1			Hydrogen bromide		2		1	Phosphine	1			
Butyl mercaptan	2	1			Hydrogen chloride		2		1	Putrescine	1	2		
Butylene	2	1			Hydrogen cyanide	1				Pyridine (!)	1	1		
Butyne	2	1			Hydrogen fluoride	1			1	Skatole	2	1		

Table 2.5 Media Selection by Contaminant [2015A, Ch546, Tbl 7] *(Continued)*

Gaseous Contaminant	PIA	AC	AIC	BIC	Gaseous Contaminant	PIA	AC	AIC	BIC	Gaseous Contaminant	PIA	AC	AIC	BIC
Butyraldehyde	2	1			Hydrogen iodide	2				Silane	1			
Butyric acid		1		2	Hydrogen selenide					Stoddard solvent	1			
Cadaverine	2	1			Hydrogen sulfide	1			1	Stibine	1			
Camphor		1			Iodine		1			Styrene (!)	2	1,1		
Carbon dioxide (CO_2)	Carbon w/catalyst				Iodoform	2	1			Sulfur dioxide	1			1
Carbon disulfide	2	1			Isopropanol	2	1			Sulfur trioxide	1			1
Carbon monoxide (CO)	Carbon w/catalyst				Kerosene		1			Sulfuric acid		2		1
Carbon tetrachloride		1			Lactic acid		1			Toluene		1		
Chlorine (Cl_2)				1	Menthol	2	1			Triethylamine		2	1	
Chloroform		1			Mercury vapor		Impreg. AC			Trichlorethylene		1		
Creosote (!)	1,2	2,1			Methanol	2	1			1,1,1, trichloroethane (!)	1	2,1		
Cyclohexane		1			Methyl acrylate	2	1			R-11 (see below)		1		
Cyclohexanol	2	1			Methyl bromide (!)	2,1	1			Turpentine	2	1		
Cyclohexanone	2	1			Methyl butyl ketone (!)	1,2	2,1			Urea (!)	2	1,1		
Cyclohexene		1			Methyl cellosolve acetate	2	1			Uric acid (!)	1	1		2,2
Decane		1			Methylchloroform		1			Vinyl chloride		1		
Diborane	1				Methylcyclohexane		1			Xylene		1		
Dichlorobenzene		1			Methylene chloride		1							

1 = primary media selection for contaminant; 2 = secondary media selection.
PIA = permanganate-impregnated alumina; AC = activated carbon; AIC = acid-impregnated carbon; BIC = base-impregnated carbon.
R-114 is dichlorotetrafluoroethane; R-11 is trichlorofluoromethane.

Comments: Some contaminant molecules have isomers that, because they have different physical properties (boiling point, vapor pressures), require different treatment methods. For some contaminants, preferred treatment is ion exchange or another (nonlisted) impregnated carbon. For some contaminants, manufacturer recommendations differ. "!" is used to identify these cases.

Table 2.6 Example Generation of Gaseous Contaminants by Building Materials [2015A, Ch 46, Tbl 2]

Contaminant	Emission Factor Averages (ranges), μg/(h·m²)					
	Acoustic Ceiling Panels	Carpets	Fiberboards	Gypsum Boards	Paints on Gypsum Board	Particle Boards
4-Phenylcyclo-hexene (PCH)		8.4 (n.d.- 85)				
Acetaldehyde		2.8 (n.d.- 37)	9.0 (n.d.-32)			28 (n.d.-55)
Acetic acid			8.4 (n.d.-26)			
Acetone	12 (n.d.-33)		35 (n.d.-67)	37 (n.d.-110)	35 (n.d.-120)	
Ethylene glycol			140 (n.d.-290)		19 (n.d.-190)	160 (140-200)
Formaldehyde	5.8 (n.d.-25)	3.6 (n.d.- 41)	220 (n.d.-570)	6.8 (n.d.-19)		49 (n.d.-97)
Naphthalene		11 (n.d.-59)	3.0 (n.d.-8.2)			
n-Heptane			21 (n.d.-53)			
Nonanal	4.9 (1.7-11)	11 (n.d.-68)		10 (n.d.-28)	3.7 (n.d.-24)	
Toluene			19 (n.d.-46)			
TVOC*	32 (3.2-150)	1900 (270-9100)	400 (52-850)	15 (n.d.-61)	2500 (170-6200)	420 (240-510)

Table 2.6 Example Generation of Gaseous Contaminants by Building Materials [2015A, Ch 46, Tbl 2] ***(Continued)***

Contaminant	Emission Factor Averages (ranges) in $\mu g/(h \cdot m^2)$					
	Plastic Laminates and Assemblies	Non-Rubber-Based Resilient Flooring	Rubber-Based Resilient Flooring	Tackable Wall Panels	Thermal Insulations	Wall Bases (Rubber-Based)
1,2,4-Trimethylbenzene			210 (n.d.-590)			
2-Butoxy-ethanol		2.7 (n.d.- 24)	1.6 (n.d.-24)			
Acetaldehyde		11 (n.d.- 49)				
Acetone	75 (4.8-150)	120 (n.d.- 830)			12 (1.8-21)	220 (30-400)
Butyric acid		0.51 (n.d. - 5.1)				
Dodecane			1.3 (n.d.-20)			
Ethylene glycol		38 (n.d.- 210)				
Formaldehyde	13 (n.d.-29)	6.8 (n.d.- 79)			5.9 (0.35-14)	32 (3.6-61)
Naphthalene		3.4 (n.d.- 14)	5.6 (n.d.-28)	6.6 (6.6)		
n-Butanol						100 (n.d.-200)
Nonanal		5.7 (n.d.- 19)	1.4 (n.d.-11)		1.8 (0.57-4)	
Octane						150 (n.d.-300)
Phenol	9.4 (4.4-19)	35 (n.d.- 310)				340 (n.d.-680)
Toluene		5.1 (n.d.- 12)				
Undecane						140 (13-270)
TVOC*	160 (6.3-310)	680 (100-2100)	15000 (1500-100000)	270 (100-430)	7.5 (0.57-26)	7100 (1200-13000)

Source: Material Emissions Study, California Integrated Waste Management Board, Publication 433-03-015, 2003.
n.d. = nondetectable
* TVOC concentrations calculated from total ion current (TIC) from GC/MS analysis by adding areas of integrated peaks with retention times greater than 5 min, subtracting from sum of area of internal standard chlorobenzene-d5, and using response factor of chlorobenzene-d5 as calibration.

Kitchen Ventilation

From ASHRAE Standard 154-2016, *Ventilation for Commercial Cooking Operations*

(See complete standard for detailed guidance.)

This section provides guidance on hoods used in commercial kitchens. For information on laboratory applications, see Chapter 16 of the 2015 *ASHRAE Handbook—HVAC Applications*; also see *ASHRAE Laboratory Design Guide*. For cleanroom applications, see *ASHRAE Design Guide for Cleanrooms*; also see Chapter 18 of the 2015 *ASHRAE Handbook—HVAC Applications*.

3. DEFINITIONS

air curtain supply: see *replacement air, makeup air (dedicated replacement air)*, *air curtain*.

appliance: a cooking device or apparatus used in a kitchen that consumes energy provided by gas, electricity, solid fuel, steam, or another fuel source.

appliance duty level: an appliance rating category based on the exhaust airflow required to capture, contain, and remove the cooking effluent and products of combustion under typical operating conditions with a nonengineered wall-mounted canopy hood (based on ASHRAE RP-1362). This is different from the historical approach, in which duty levels were based on the temperature of the cooking surface. The following appliance duty classifications are used in this standard:

a. ***light:*** a cooking process requiring an exhaust airflow rate of less than 310 L/s/m for capture, containment, and removal of the cooking effluent and products of combustion.
b. ***medium:*** a cooking process requiring an exhaust airflow rate of 310 to 460 L/s/m for capture, containment, and removal of the cooking effluent and products of combustion.
c. ***heavy:*** a cooking process requiring an exhaust airflow rate of 460 to 620 L/s/m for capture, containment, and removal of the cooking effluent and products of combustion.
d. ***extra-heavy:*** a cooking process requiring an exhaust airflow rate greater than 620 L/s/m for capture, containment, and removal of the cooking effluent and products of combustion.

approved: acceptable to the authority having jurisdiction.

back-wall supply: see *replacement air*, *makeup air (dedicated replacement air)*, *back-wall*.

baffle filter: see *grease removal device*.

capture area: the area within an exhaust hood that contains cooking effluent until it is exhausted.

capture and containment (C&C): an exhaust hood's ability to capture and contain the cooking effluent and heat generated during cooking operations.

cartridge filter: see *grease removal device*.

centrifugal fan: see *exhaust fan*.

certified: see *listed*.

compensating hood: see *replacement air*, *makeup air (dedicated replacement air)*, *internal*.

commercial cooking appliance: an appliance specifically designed to be used in a food-service-establishment kitchen, such as, but not limited to, a restaurant or cafeteria kitchen. Appliances designed for residential use shall be treated as commercial appliances when installed in commercial food-service establishments.

condensate hood: see *hood, Type II hood*.

cooking effluent: the emissions generated by cooking appliances during their operation; for example, convective heat, moisture, vapor, products of combustion, smoke, and particulate matter.

demand-control ventilation: a ventilation system that utilizes an automatically controlled variable-speed device, such as a multispeed fan or variable-speed drive, to modulate the exhaust airflow rates in response to the variation in cooking load.

duct: a conduit for conveying cooking effluent from the hood to the outdoors or for conveying replacement air into a room or space.

ductless hood: see *recirculating hood*.

end skirt: see *side panel*.

exfiltration: leakage or flow of indoor air out of the building or space through openings in the building or space envelope, whether intentional or unintentional. The driving force for exfiltration is a positive pressure in the building or space relative to the exterior of the building envelope.

exhaust fan: a fan used to exhaust cooking effluent collected by a hood. Also referred to as a *power roof ventilator*. The majority of these fans have a centrifugal fan wheel. Fans used in Type I hood applications must include provisions for handling grease and access for cleaning.

a. ***in-line exhaust fan* or *tubular centrifugal fan:*** a fan designed for mounting indoors or outdoors in a section of duct between the hood and the point of discharge. Air enters the fan axially and discharges linear to the entrance.
b. ***roof exhaust fan* or *power roof ventilator:*** a fan designed for curb mounting on a roof and that discharges downward toward the roof, vertically up away from the roof, or horizontally away from the building. Fans that discharge downward may be used only for Type II hood applications.
c. ***up-blast exhaust fan:*** a fan designed for curb-mounting on a roof or for wall mounting. Air enters the fan axially but discharges radially from the centrifugal impeller and turns 90 degrees to exit the fan vertically where roof-mounted and horizontally where wall-mounted.
d. ***side-wall exhaust fan:*** a fan design similar to an up-blast exhaust fan but designed to mount outdoors on the side wall of a building. The mounting arrangement and internal construction may be specific to side discharge orientation. The fan discharges horizontally away from the building.
e. ***utility-set exhaust fan:*** a fan typically designed with a single-inlet, a scroll housing, and a backward-inclined or an airfoil centrifugal impeller. It can provide a higher static efficiency capability than a typical power roof ventilator. Air enters the impeller axially and leaves it in a substantially radial direction. These can be mounted indoors or outdoors in-line having additional duct between the fan outlet and the point of discharge.

exhaust fire (actuated) damper: a damper arranged to automatically close to restrict the passage of fire airflow into the exhaust duct.

fire resistance rating: the time rating of a material or assembly indicating its ability to withstand exposure to a fire.

fire suppression system: an automatic fire suppression system that is specifically designed to protect Type I hood systems and, where required, the cooking appliances served by the hood system(s).

front-face supply: see *replacement air*, *makeup air (dedicated replacement air)*, *front-face*.

grease duct: a duct system for the conveyance of cooking effluent. The system is designed and installed to reduce the accumulation of combustible condensation, thus reducing the possibility of fire within the duct system.

grease laden: containing grease particles and/or grease vapor.

grease removal device: a device designed and installed in a Type I hood to remove grease vapor and/or particles from the airstream. As used in this standard, the term refers to devices that are certified to UL Standard 1046, *Grease Filters for Exhaust Ducts*, or to UL Standard 710, *Exhaust Hoods for Commercial Cooking Equipment*, as part of the hood. Devices include but are not limited to the following:

a. ***baffle filter:*** a filter typically having a series of vertical baffles designed to capture grease and drain to a grease trough. Filters are removable for cleaning and maintenance of the hood.

b. ***cartridge filter:*** a filter having a horizontal slot opening with a series of internal deflectors designed to capture grease and drain to a grease trough. Filters are removable for cleaning and maintenance of the hood.

c. ***fixed or stationary extractor:*** a device typically having horizontal slot openings with a series of internal deflectors designed to capture grease and drain to a grease trough. Extractors are not removable from the hood and typically have access doors for cleaning and maintenance of the hood.

d. ***multistage extractor or filter:*** these devices consist of a series of two or more grease removal devices located in the hood.

e. ***removable extractor:*** any style of grease removal device that is removable from the hood.

f. ***water wash:*** a version of the fixed extractor that has a system of built-in nozzles for cleaning the grease removal device.

greasetight: designed to prevent the leakage of grease under normal operating conditions.

hood: a device designed to capture and contain cooking effluent, including grease, smoke, steam, heat, and vapor, until it is exhausted through a duct or recirculating system. Hoods are categorized as Type I or Type II.

Type I hood: a hood used for collecting and removing convective heat, grease particulate, condensible vapor, and smoke. This category includes listed grease filters, baffles, or extractors for removing the grease and a fire-suppression system. Type I hoods are installed over cooking appliances, such as ranges, fryers, griddles, broilers, and ovens, that produce smoke or grease-laden vapors. For Type I hoods, the following types of hoods are commonly available.

a. ***wall-mounted canopy hood:*** a wall canopy exhaust hood is mounted against a wall above a single appliance or a line of appliances, or it may be freestanding with a vertical back panel extending from the rear of the appliance(s) to the hood. It typically overhangs the front and sides of the appliance(s) on all open sides of the hood. The wall acts as a back panel, forcing replacement air to be drawn across the front and/or side(s) of the cooking appliance, thus increasing the effectiveness of the hood to capture and contain effluent generated by the cooking operations. Mounting height varies.

b. ***single-island canopy hood:*** a single-island canopy hood is placed over a single appliance or line of appliances. It is open on all sides and overhangs the front, rear, and sides of the appliance(s). A single-island canopy is more susceptible to cross drafts and requires greater exhaust airflow than an equivalent-sized wall-mounted canopy to capture and contain effluent generated by the cooking operations. Mounting height varies.

c. ***double-island canopy hood:*** a double-island canopy hood is placed over back-to-back appliances or lines of appliances. It is open on all sides and overhangs the front and the sides of the appliance(s). It may have a wall panel between the backs of the appliances. Mounting height varies.

d. ***backshelf hood:*** also referred to as a *noncanopy hood*, *low-proximity hood*, or *sidewall hood* (where wall mounted). Its front lower lip is low over the appliance(s) and is typically set back from the front of the appliance(s), which means there may be no front overhang of appliance(s). It is always closed to the rear of the appliances by a panel where freestanding or by a panel or wall when wall mounted, and its height above the cooking surface varies. This style of hood can be constructed with partial end panels to increase its effectiveness in capturing the effluent generated by the cooking operations.

e. ***eyebrow hood:*** an eyebrow hood is mounted directly to the face or top of an appliance above the opening(s) or door(s) from which effluent is emitted, overhanging the front of the opening(s) to capture the effluent. Mounting height is fixed.

f. ***pass-over hood:*** a pass-over hood is a backshelf hood constructed and installed low enough to allow food to be passed over the top. Mounting height varies.

g. ***ventilated ceiling hood:*** typically installed so that the bottom edge of the hood is flush with the ceiling height.

h. ***recirculating hood:*** a hood with an integral or non-integral electric cooking appliance to capture and contain cooking effluent, consisting of a fan, air filtering system, and a fire extinguishing system.

Type II hood: a hood that collects and removes steam, heat, and products of combustion where grease or smoke is not present. It may or may not have grease filters or baffles and is not designed to have a fire-suppression system. A Type II hood can be used where the cooking operation from each appliance underneath the hood does not produce grease in excess of 5 mg/m^3 when measured at 236 L/s exhaust airflow.

hood type: see *hood*, *Type I hood* and *hood, Type II hood*.

infiltration: see *replacement air*, *infiltration*.

interlock, direct: the direct connection between equipment, such as between a common circuit, relays, etc.

interlock, indirect: the indirect connection between equipment through an external controller; for example, a timeclock, building automation system, heat sensor, etc.

internal discharge makeup air: see *replacement air*, *makeup air (dedicated replacement air)*, *internal*.

labeled: equipment or materials to which a label, symbol, or other identifying mark of an organization, acceptable to the authority having jurisdiction, has been attached. This organization is concerned with product evaluation and maintains periodic inspection of the production of labeled equipment or materials. By labeling the equipment or materials, the manufacturer indicates compliance with appropriate standards or performance in a specified manner.

liquid-tight: constructed and performing so as not to permit the leakage of any liquid at any temperature.

listed: equipment or materials included in a list published by an organization acceptable to the authority having jurisdiction. This organization is concerned with product evaluation and performs periodic inspections of production of listed equipment or materials. The list states either that the equipment or material meets appropriate standards or that it has been tested and found suitable for use in a specified manner.

makeup air: see *replacement air*, *makeup air (dedicated replacement air)*.

mounting height: typically the height above the finished floor at which the bottom front edge of a canopy or noncanopy hood is mounted. Listed hoods are typically rated at the minimum and maximum heights above the cooking surface at which they may be mounted.

multiple-hood exhaust system: a system in which more than one hood is connected to a common exhaust duct and fan system.

multistage extractor: see *grease removal device*.

net exhaust flow rate: the exhaust flow rate for a hood, minus any internal discharge makeup airflow rate.

overhang: the horizontal distance that the lower front edge of the hood extends beyond the top horizontal cooking surface of the appliance.

outdoor air: the air outside of a building or air taken from the outdoors and not previously circulated through an HVAC system.

packaged: provided by a manufacturer or vendor in a substantially complete and operable condition.

power roof ventilator: see *exhaust fan.*

recirculating system: systems for control of smoke and grease-laden vapors from commercial cooking appliances that do not exhaust to the outdoors.

replacement air: outdoor air that is used to replace air removed from a building through an exhaust system. Replacement air may be derived from one or more of the following: makeup air, supply air, transfer air, and infiltration. However, the ultimate source of all replacement air is outdoor air.

***makeup air* (*dedicated replacement air*):** air deliberately brought into the building from the outdoors and supplied to the vicinity of an exhaust hood to replace the air and cooking effluent being exhausted. Makeup air is generally filtered and fan-forced, and it may be heated or cooled depending on the requirements of the application. Makeup air may be delivered through outlets integral to the exhaust hood (compensating hoods) or through outlets in the same room. Following are systems commonly used to supply makeup air.

a. ***air curtain:*** air that is introduced vertically downward through a slot, louvers, or holes along the front edge of the hood or around the perimeter of the hood. This design has also been referred to as *down-discharge*.
b. ***back-wall:*** air that is introduced behind and/or below the cooking equipment. A makeup air plenum is installed between the back of the hood and the wall. The full-length plenum typically extends down the wall to approximately 6 in. (150 mm) below the cooking surface or 2 to 3 ft (600 to 900 mm) above the floor. The air supplied by this system mostly enters the kitchen space rather than remain contained in the cooking zone.
c. ***front-face:*** air that is introduced either horizontally or at a slight downward angle from horizontal from the front of the hood plenum.
d. ***internal:*** typically in this design, untempered makeup air is introduced directly into the hood cavity. This design has also been referred to as *short-circuit*.
e. ***perimeter:*** makeup air is discharged vertically downward from a plenum above and outside of the front and sides of the hood.

supply air: air entering a space from an air-conditioning, heating, or ventilating system for the purpose of comfort conditioning. Supply air is generally filtered, fan-forced, and heated, cooled, humidified, or dehumidified as necessary to maintain specified temperature and humidity conditions. Only the quantity of outdoor air within the supply airflow is used as replacement air. Following are systems commonly used for delivering supply air.

a. ***louvered ceiling diffusers:*** ceiling-installed, aspirating, two-, three-, or four-way diffusers. Air should not be directed toward the hood.
b. ***perforated diffusers:*** a ceiling-installed diffuser with a perforated face. Air should not be directed toward the hoods.
c. ***linear slot diffusers:*** ceiling-installed diffusers, typically placed around the perimeter of rooms. These have a higher discharge velocity than a louvered ceiling.
d. ***displacement diffusers:*** floor-, wall-, and ceiling-mounted diffusers with perforated face areas providing laminar low-velocity flow from the face.

transfer air: air transferred from one room to another through openings in the room envelope, whether it is transferred intentionally or not. The driving force for transfer air is generally a small pressure differential between the rooms, although one or more fans may be used. Only that portion of air transferred from another room that originated as outdoor air may be considered transfer air.

infiltration: leakage or flow of outdoor air into the building or space through openings in the building or space envelope, whether intentional or unintentional. The driving force for infiltration is a negative pressure in a space or building relative to the exterior of the building envelope.

setback: the horizontal distance that the top horizontal cooking surface of an appliance extends beyond the front edge of a backshelf or pass-over hood.

short-circuit makeup air: see *replacement air*, *makeup air (dedicated replacement air)*, *internal*.

side panel: a panel that is attached to the lower edge of the end wall of a hood effectively extending the side of the hood down closer to the cooking appliance.

smoke bomb: a device that combusts to produce a large volume of smoke, greater than 189 L/s.

***smoke candle* or *smoke puffer*:** a device that is ignited and combusts to produce smoke or uses a chemical interaction (such as titanium tetrahydrochloride [$TiCL_4$] with humid air) to produce smoke or that emits a silica powder to produce smoke.

solid-fuel cooking appliance: an appliance that combusts a solid fuel such as wood, charcoal, or coal to provide all or part of the heat for the cooking process.

solid-fuel flavoring cooking appliance: an appliance that uses an energy source other than solid fuel to provide all of the heat for the cooking process and also combusts solid fuel solely for the purpose of imparting flavor to the food being cooked.

supply air: see *replacement air*, *supply air.*

transfer air: see *replacement air*, *supply air*.

tubular centrifugal fan: see *exhaust fan*, *tubular centrifugal fan*.

4. EXHAUST HOODS

4.1 Hood Requirements

4.1.1 Type I hoods shall be listed in accordance with UL Standard 710, UL Standard 710B, or UL Standard 710C and shall be installed in accordance with their listing requirements. Type II hoods shall meet the requirements of Sections 4.2 through 4.8. Type I hoods shall meet the requirements of Section 4.2 and Sections 4.5 through 4.8. Where a Type II hood is required, a Type II or listed Type I hood shall be provided.

4.1.1.1 Recirculating systems and recirculating hoods shall be listed in accordance with UL Standard 710B.

4.1.2 A performance test of an installed Type I hood shall be carried out as specified in Section 4.7.

4.2 Where Required

4.2.1 Table 2.7 specifies the Type I hood requirements by appliance description. Table 2.8 specifies the appliance duty classification as it relates to the Type II hood requirements.

Exception: Equipment that is listed in Table 2.8 and the additional heat and moisture loads generated by unhooded electric appliances are included in the sensible and latent cooling load calculations to determine the required capacity of the HVAC system.

4.2.2 Type II hoods shall be installed in accordance with the overhangs shown in Table 2.9 and the net exhaust airflow rates shown in Table 2.10, based on the maximum appliance duty level shown in Table 2.8 for the appliances underneath the hood. Type II hoods may also be installed where cooking or dishwashing appliances produce heat, steam, or products of combustion and do not produce grease in excess of **5 mg/m^3** when measured at an exhaust airflow of **236 L/s**.

Informative Note: The 5 mg/m^3 grease concentration when measured at 236 L/s of exhaust air is equivalent to 4.21×10^{-3} kg/h of grease generated by the cooking process.

4.2.3 A Type I hood shall be provided where a cooking operation within a commercial or institutional food service facility produces smoke or grease-laden vapors. Appliances that produce greater than **5 mg/m**^{3} of grease (when measured at **236 L/s** exhaust airflow) shall require a Type I hood. Type I hoods shall be installed in accordance with the overhangs shown in Table 2.9.

Exceptions:

1. Cooking appliances not used for commercial purposes and installed within dwelling units.
2. Appliances listed in Table 2.8 that produce less than 5 mg/m^3 of grease (when measured at 236 L/s exhaust airflow).

Informative Note: The 5 mg/m^3 grease concentration when measured at 236 L/s of exhaust air is equivalent to 4.21×10^{-3} kg/h of grease generated by the cooking process.

4.2.4 Solid-Fuel Cooking Appliances. Exhaust hood systems, including hoods, ducts, and exhaust fans, serving one or more solid-fuel cooking appliances shall be independent of all other exhaust systems.

Exception: Cooking processes that only use solid fuel for flavoring are exempt from this requirement.

4.3 Type II Hood Sizing

4.3.1 Type II hood overhangs and setbacks shall comply with Table 2.9 on all open sides, measured in the horizontal plane from the inside edge of the hood to the edge of the top horizontal surface of the appliance. The vertical distance between the front lower lip of the hood and appliance cooking surface shall not exceed 1219 mm.

Exception: A side overhang is not required where full side panels or panels angled from the front lip of the hood to the front of the appliance at cooking-surface height are installed (see Figure 2.2).

4.3.2 The spaces between appliances, the backs of appliances, and the spaces from the appliances to walls or end panels shall be included in overall hood dimensions. In the case of island hoods, appliance flues shall be included in the cooking surface dimensions.

4.3.3 Hoods shall be mounted above the cooking surface as follows:

4.3.3.1 Canopy Type Hood. The vertical distance between the front lower edge of the hood and the cooking surface shall not exceed 219 mm. The vertical distance between the front lower edge of the hood and the finished floor shall not be less than 1981 mm. The inside hood height shall be at least 610 mm.

4.3.3.2 Eyebrow Type Hood. The front lower edge of the hood shall be at least 1981 mm above the finished floor.

4.3.3.3 Backshelf/Pass-Over Type Hood. The vertical distance between the front lower edge of the hood and the cooking surface shall be a maximum of 610 mm above the cooking surface.

4.4 Type II Hood Airflow Rates

4.4.1 The net exhaust flow rate (see definition in Section 3) for Type II hoods shall comply with Table 2.10. The duty level for the hood shall be the duty level of the appliance that has the highest (heaviest) duty level of all the appliances that are installed underneath the hood according to Table 2.8.

Exception: Type II hoods that are shown by the performance test in Section 4.7 to provide equivalent capture and containment at lower airflow rates.

4.5 Internal Discharge Makeup

4.5.1 Where a Type I or Type II hood has internal discharge makeup air, the makeup airflow shall not exceed 10% of the exhaust airflow. The exhaust airflow required to meet this standard shall be the net exhaust from the hood, calculated as follows:

$$E_{NET} = E_{HOOD} - MA_{ID} \tag{2.1}$$

where

E_{NET} = net hood exhaust, L/s
E_{HOOD} = total hood exhaust, L/s
MA_{ID} = makeup air, internal discharge, L/s

4.6 Type I Hood Grease Extraction

4.6.1 Type I hoods shall be provided with a grease removal device in accordance with their listing.

4.6.2 For grease removal devices that report grease removal efficiency, the efficiency data shall be reported as determined by ASTM F2519.

4.7 Hood Performance Test

4.7.1 Type II Hood Performance Test. A performance test shall be conducted upon the completion of—and before final approval of—installation of a ventilation system serving commercial cooking appliances. The test shall verify the rate of exhaust airflow required by Section 4.2. The permit holder shall furnish the necessary test equipment and devices required to perform the tests.

4.7.2 Type I Hood Capture and Containment Test. The permit holder shall verify the capture and containment performance of Type I hoods. A field test shall be conducted with all appliances under the hood at operating temperatures, all the hoods operating at design airflows, and with all sources of replacement air operating at design airflows for the restaurant. Capture and containment shall be verified visually by observing smoke or steam produced by actual cooking operation or by simulating cooking using devices such as smoke candles or smoke puffers. Smoke bombs shall not be used.

Informative Note: Smoke bombs typically create new effluent from a point source and do not necessarily show whether the cooking effluent is being captured. Actual cooking at the normal production rate is the most reliable method of generating smoke.

Table 2.7 Type I Hood Requirements by Appliance Type [Std 154-2016, Tbl 1]

Appliance Description	Size	Type I Hoods[a] Light Duty	Medium Duty	Heavy Duty	Extra-Heavy Duty
Braising pan/tilting skillet, electric	All	•			
Oven, baking, electric and gas	All	•			
Oven, rotisserie, electric and gas	All	•			
Oven, combination, electric and gas	All	•			
Oven, convection, full-size, electric and gas	All	•			
Oven, convection, half-size, electric and gas (protein cooking)	All	•			
Oven, conveyor, electric	All	•			
Oven, deck, electric and gas	All	•			
Oven, duck, electric and gas	All	•			
Oven, revolving rack, electric and gas	All	•			
Oven, rapid cook, electric	All	•			
Oven, roasting, electric and gas	All	•			
Oven, rotisserie, electric and gas	All	•			
Oven, stone hearth, gas	All	•			
Range, cook-top, induction	All	•			
Range, discrete element, electric (with or without oven)	All	•			
Salamander, electric and gas	All	•			
Braising pan/tilting skillet, gas	All		•		
Broiler, chain conveyor, electric	All		•		
Broiler, electric, underfired	All		•		
Fryer, doughnut, electric and gas	All		•		
Fryer, kettle, electric and gas	All		•		
Fryer, open deep-fat, electric and gas	All		•		
Fryer, pressure, electric and gas	All		•		
Griddle, double-sided, electric and gas	All		•		
Griddle, flat, electric and gas	All		•		
Oven, conveyor, gas	All		•		
Range, open burner, gas (with or without oven)	All		•		
Range, hot top, electric and gas	All		•		
Smoker, electric and gas	All		•		
Broiler, chain conveyor, gas	All			•	
Broiler, electric and gas, over-fired (upright)	All			•	
Broiler, gas, underfired	All			•	
Grill, plancha, electric and gas	All			•	
Oven, tandoor, gas	All			•	
Range, wok, gas and electric	All			•	
Oven, stone hearth, wood-fired or wood for flavoring	All				•
Solid fuel cooking appliances combusting a solid fuel (such as wood, charcoal, or coal) to provide all or part of the heat for the cooking process[b]	All				•

[a]Where recirculating systems or recirculating hoods are used, the additional heat and moisture loads generated by such appliances shall be accounted for in the sensible and latent loads for the HVAC system.
[b]Solid-fuel flavoring cooking appliances shall comply with this table as if they do not combust solid fuel.

Table 2.8 Type II Hood Requirements by Appliance Description
[Std 154-2016, Tbl 2]

Appliance Description	Size	Hood Not Required[a]	Type II Hoods[b] Light Duty	Type II Hoods[b] Medium Duty
Cabinet, holding, electric	All	•		
Cabinet, proofing, electric	All	•		
Cheese-melter, electric	All	•		
Coffee maker, electric	All	•		
Cooktop, induction, electric	All	•		
Dishwasher, door-type rack, hot water sanitizing, heat recovery and vapor reduction, electric	All	•		
Dishwasher, door-type rack, chemical sanitizing, heat recovery and vapor reduction, electric	All	•		
Dishwasher, door-type dump and fill, hot water sanitizing, electric	All	•		
Dishwasher, door-type dump and fill, chemical sanitizing, electric	All	•		
Dishwasher, pot and pan, hot water sanitizing, heat recovery and vapor reduction, electric	All	•		
Dishwasher, powered sink, electric	All	•		
Dishwasher, under-counter, chemical sanitizing, electric	All	•		
Dishwasher, under-counter, electric	All	•		
Dishwasher, undercounter, hot water sanitizing, heat recovery and vapor reduction, electric	All	•		
Drawer warmer, 2 drawer, electric	All	•		
Egg cooker, electric	All	•		
Espresso machine, electric	All	•		
Grill, panini, electric	All	•		
Hot dog cooker, electric	All	•		
Hot plate, countertop, electric	All	•		
Ovens, microwave, electric	All	•		
Popcorn machine, electric	All	•		
Rethermalizer, electric	All	•		
Rice cooker, electric	All	•		
Steam table, electric	All	•		
Steamers, bun, electric	All	•		
Steamer, compartment atmospheric, countertop, electric	All	•		
Steamer, compartment pressurized, countertop, electric	All	•		
Table, hot food, electric	All	•		
Toaster, electric	All	•		
Waffle iron, electric	All	•		
Kettle, steam jacketed, tabletop, electric, gas and direct steam	<20 gallons		•	
Oven, convection, half-size, electric and gas (non-protein cooking)	All		•	
Pasta cooker, electric	All		•	
Rethermalizer, gas	All		•	

Table 2.8 Type II Hood Requirements by Appliance Description [Std 154-2016, Tbl 2] *(Continued)*

Appliance Description	Size	Hood Not Required[a]	Type II Hoods[b]	
			Light Duty	Medium Duty
Rice cooker, gas	All		•	
Steamer, atmospheric, gas	All		•	
Steamer, pressurized, gas	All		•	
Steamer, atmospheric, floor-mounted, electric	All		•	
Steamer, pressurized, floor-mounted, electric	All		•	
Kettle, steam-jacketed floor mounted, electric, gas, and direct steam	<20 gal		•	
Dishwasher, conveyor rack, chemical sanitizing	All			•
Dishwasher, conveyor rack, hot water sanitizing	All			•
Dishwasher, door-type rack, chemical sanitizing	All			•
Dishwasher, door-type rack, hot water sanitizing	All			•
Dishwasher, pot and pan, hot water sanitizing	All			•
Pasta cooker, gas	All			•
Steam-jacketed kettle, floor mounted, electric and gas	≥20 gal			•

[a]Where hoods are not required, the additional heat and moisture loads generated by such appliances shall be accounted for in the sensible and latent loads for the HVAC system.
[b]Where recirculating systems or recirculating hoods are used, the additional heat and moisture loads generated by such appliances shall be accounted for in the sensible and latent loads for the HVAC system.

Table 2.9 Minimum Overhang Requirements for Type II Hoods [Std 154-2016, Tbl 3]

Type of Hood	End Overhang, mm	Front Overhang, mm	Rear Overhang, mm
Wall-mounted canopy	152	305	N/A
Single-island canopy	305	305	305
Double-island canopy	305	305	N/A
Eyebrow	N/A	305	N/A
Backshelf/proximity/pass-over	152	254 (setback)	N/A

N/A = Not Applicable

Table 2.10 Type II Hood Minimum Net Exhaust Airflow Rates [Std 154-2016, Tbl 4]

Type of Hood	Minimum Net Exhaust Flow Rate per Linear Hood Length, L/s/m	
	Light Duty Equipment	Medium Duty Equipment
Wall-mounted canopy	310	465
Single island	620	775
Double island	388	388
Eyebrow	388	388
Backshelf (pass-over)	310	465

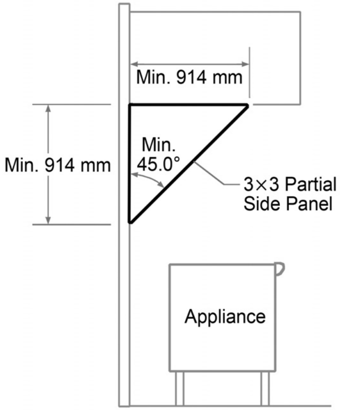


Figure 2.2 914 × 914 mm partial side panel [Std 154-2016, Fig 1]

4.8 Hood Clearance to Combustibles

4.8.1 Type I hoods shall be installed with a minimum 457 mm clearance to combustibles from any hood surface.

Exception: Type I hoods that are listed to reduced clearances in accordance with Standard UL710 or Standard UL 710B shall be installed at a minimum clearance to combustibles in accordance with their listings.

5. EXHAUST SYSTEMS

5.1 Duct Systems

5.1.1 Ducts serving Type I hoods shall be constructed of carbon steel of a minimum 16 gage thickness or stainless steel of a minimum 18 gage thickness. All seams, joints, and penetrations shall have a liquid-tight continuous external or internal weld. Internal welds shall be flush with the duct walls and accessible for inspection.

Exception: Factory-built ducts listed in accordance with UL 1978.

5.1.2 Ducts shall be constructed and installed so that grease cannot collect in any portion thereof, and ducts shall slope not less than one-fourth unit vertical in 12 units horizontal (2% slope) toward the hood or toward an approved grease reservoir. Where horizontal ducts exceed 75 ft (22.8 m) in length, the slope shall not be less than one unit vertical in 12 units horizontal (8.3% slope).

Exception: Listed factory-built ducts constructed of a round cross section shall be permitted to be installed at a reduced slope as allowed by their listing and the manufacturer's installation instructions.

5.1.3 Ducts shall not pass through firewalls unless enclosed in accordance with the applicable codes and standards.

5.1.4 Ducts shall lead to the exterior of the building.

5.1.5 A separate grease duct system shall be provided for each Type I hood. A separate grease duct system is not required where all of the following conditions are met:

a. All interconnected hoods are located within the same story.
b. All interconnected hoods are located within the same room or in adjoining rooms.
c. Interconnecting ducts do not penetrate fire barriers.
d. The grease duct system does not serve solid fuel-fired appliance(s).

5.1.6 Ducts shall be installed without forming dips or traps that might collect grease, except where unavoidable. In such situations, the duct section having a dip or trap shall be provided with drain access for regular cleanout.

Informative Note: For other duct construction and installation details, such as welded duct connections, access openings for inspection and maintenance, clearance to combustible material, interior installation (including fire-rated enclosures and the clearance between the duct and interior surface of the enclosures), exterior installation, and exhaust system termination on the roof or at a wall, refer to NFPA 96, the *International Mechanical Code*, or local codes.

5.1.7 Ducts with field-applied insulation listed in accordance with ASTM E 2336, *Standard Test Methods for Fire Resistive Grease Duct Enclosure Systems*, and factory-built ducts with integral insulation listed in accordance with UL 2221, *Tests of Fire Resistive Grease Duct Enclosure Assemblies*, are acceptable, where included in NFPA 96, the *International Mechanical Code*, or the *Uniform Mechanical Code* for use as an alternative to a duct and fire-resistance-rated shaft enclosure around the duct.

5.2 Duct Leakage Testing

5.2.1 Prior to the use or concealment of any portion of a grease duct system, a leakage test shall be performed to determine that all welded joints and seams are liquid tight. The leakage test shall consist of a light test, water pressure test, or an approved equivalent test. The permit holder shall be responsible for providing the necessary equipment and for performing the test.

5.2.1.1 Light Test. The light test shall be performed by passing a lamp having a power rating of not less than 100 W through the entire section of ductwork to be tested. The lamp shall be open so as to emit light equally in all directions perpendicular to the duct walls. No light from the duct interior shall be visible through any exterior surface.

5.2.1.2 Water Test. The water test shall be performed by use of a pressure washer operating at a minimum of 10.34 kPa, simulating cleaning operations. The water shall be applied directly to all areas to be tested. No water applied to the duct interior shall be visible on any exterior surface in any volume during the test.

5.3 Airflow Performance

5.3.1 The velocity in the duct shall be at least 2.54 m/s.

Informative Note: This standard does not limit the airflow velocity by specifying a maximum velocity, but due to typical spatial and cost constraints, general design duct velocities between 7.62 and 9.14 m/s are often used when designing for maximum airflows. Duct velocities greater than 12.70 m/s can cause unwanted duct pressure and noise levels.

5.3.2 Lower exhaust airflow than that required for full-load cooking conditions is permitted during no-load cooking conditions, where engineered controls or listed multispeed or variable-speed controls automatically operate the exhaust system to maintain capture and removal of cooking effluents.

5.4 Fans

5.4.1 Fans shall be of sufficient capacity to provide the required airflow against the system's resistance. Expected air temperatures, altitude, windage, and system effects shall be taken into account when determining fan capacity. Fan air performance shall be tested and certified according to AMCA Standard 210.

Informative Note: Belt-drive fans and adjustable-drive sheaves provide a means of adjusting the fan speed for final system balancing. A variable-speed controller allows a broader range of speed adjustability.

5.4.2 Exhaust fans (up-blast, in-line, or utility-set fans) serving Type I hoods shall be capable of handling hot, grease-laden air and flare-up conditions. Fans shall be designed to contain and properly drain grease removed from the airstream. The fan housing or scroll that contains the grease shall be fully welded so that it is liquid tight. The fan impeller shall be a self-cleaning design.

Exception: Fans that are listed to UL 705, *Standard for Power Ventilators*, and UL 762, *Outline of Investigation for Power Roof Ventilators for Restaurant Exhaust Applications*.

5.4.3 Up-blast fans shall be hinged with tip-over restraints and have a flexible weatherproof electrical cable to permit inspection and cleaning. Utility-set exhaust fans shall be provided with access panels for inspection and cleaning.

5.4.4 Access shall be provided for cleaning the fan wheel. The access opening shall be a minimum of 76 × 127 mm or have a circular diameter of at least 102 mm on the curvature of the outer fan housing. Fan drive assemblies shall be separated from the airstream. Covers shall be provided with motor weather protection for outdoor installation and belt guards for indoor applications.

5.4.5 The ductwork extending to up-blast fans shall extend a minimum of 457 mm above the roof surface.

5.5 Other Equipment

5.5.1 Thermal recovery units, air pollution control devices, or other devices can be used in the exhaust systems when specifically approved for such use except where prohibited. Refer to Section 514.2 of the *International Mechanical Code*, for prohibited applications.

5.5.2 Clearance, installation, and fire-extinguishing system requirements shall comply with applicable codes and standards.

5.5.3 Pollution control units not equipped with electrostatic precipitators shall be listed in accordance with the applicable requirements of UL710 and UL1978. Pollution control units equipped with electrostatic precipitators shall be listed in accordance with UL867 and the applicable requirements of UL710 and UL1978.

5.6 Exhaust Discharge

5.6.1 Exhaust systems shall be designed to prevent re-entrainment into building intakes. Prevailing winds and velocities shall be considered when locating intake and exhaust openings. The minimum horizontal distance between discharge and intake shall be 3 m. Where this horizontal distance is not achievable, the exhaust shall discharge a minimum of 0.6 m above any outdoor air. Exhaust discharge shall not impinge on overhangs, parapets, other equipment, or higher parts of buildings.

Informative Note: Refer to Chapter 16 of the 2013 *ASHRAE Handbook—Fundamentals* for airflow patterns around buildings.

5.6.2 Exhaust airstreams for Type I hoods shall be located a minimum of 1016 mm above the finished roof surface and be directed away from roof and building surfaces.

5.6.3 Additional protection for roofing material at the exhaust discharge of a Type I hood shall be provided to prevent material degradation or failure.

5.7 Operation and Maintenance

5.7.1 Appliance Interlock

5.7.1.1 The exhaust fan serving a Type I hood shall have automatic controls that will activate the fan when any appliance that requires such Type I hood is turned on, or a means of interlock shall be provided that will prevent operation of such appliances when the exhaust fan is not turned on.

5.7.1.2 Where one or more temperature or energy sensors are used to activate a Type I hood exhaust fan, the fan shall activate not more than 15-minutes after the first appliance served by that hood has been turned on. A method of interlock between an exhaust hood system and appliances equipped with standing pilot burners shall not cause the pilot burners to be extinguished. A method of interlock between an exhaust hood system and cooking appliances shall not involve or depend on any component of a fire extinguishing system.

5.7.2 The entire exhaust system shall be inspected at regular intervals for grease buildup by a properly trained, qualified, and certified company or person(s) acceptable to the authority having jurisdiction.

5.7.2.1 The schedule of inspection for grease buildup in the exhaust system and cleaning of the exhaust system shall comply with NFPA 96.

5.7.2.2 Upon inspection, if the exhaust system is found to be contaminated with grease deposits, the contaminated portions of the exhaust system shall be thoroughly cleaned by a properly trained, qualified, and certified company or person(s) acceptable to the authority having jurisdiction.

5.7.3 Inspection and maintenance of thermal recovery units, air pollution control devices, or other devices shall be conducted by properly trained and qualified persons at a frequency specified in the manufacturer's instructions or equipment listing.

6. REPLACEMENT AIR

6.1 Air Introduction

6.1.1 The terminal velocity of air introduced from devices in the kitchen shall not exceed 0.25 m/s at the lowest edges of the hood.

Informative Note:

1. Using perforated ceiling or perimeter diffusers generally results in a lower terminal velocity at the lower edge of the hood than directional ceiling diffusers.
2. Best practice is to bring conditioned air into the kitchen away from the hood and distribute it throughout the kitchen to improve worker productivity and comfort as well as to lower hood exhaust rates.

6.1.2 Transfer air from dining or other areas that passes through openings such as windows or walkways shall be sized for air velocities not to exceed 0.381 m/s based on the free area of the opening. Openings provided for transfer air shall remain open during system operation.

Informative Note: Such openings should be arranged to avoid creating drafts on personnel. Consideration should be given to minimizing air velocity when openings are used as pass-through openings for prepared food.

6.2 Air Balance

6.2.1 Design plans for a facility with a commercial kitchen ventilation system shall include a table or diagram indicating the design outdoor air balance (see Informative Annex A, Section A1). The design outdoor air balance shall indicate all exhaust and replacement air for the facility, plus the net exfiltration if applicable. The total replacement air airflow rate shall equal the total exhaust airflow rate plus the net exfiltration. It is permissible to supply replacement air to the kitchen space by using transfer air from areas other than the kitchen.

Informative Note: Although individual replacement air sources are not required to be 100% outdoor air, sufficient outdoor air must be introduced into the system to compensate for each exhaust and exfiltration component. For example, for 47 L/s transfer air from room A to room B to qualify as replacement air, at least 47 L/s outdoor air must be provided to room A (e.g., as outdoor air to an environmental air system serving room A, infiltration to room A, or transfer air from another room).

6.2.2 Operation of systems where airflows can vary (including but not limited to HVAC systems incorporating variable air volume, systems with outdoor air economizer control, or exhaust systems with variable airflow) shall be controlled to comply with the requirements of this standard over the full range of anticipated airflows. Additional air balance diagrams or tables shall be provided as necessary to indicate compliance over the full range of anticipated airflow.

6.2.3 Where the design air balance relies on transfer air from a source beyond the facility's control (e.g., air drawn into an individual tenant's facility from the common areas of a shopping mall), this source shall be identified.

6.3 Pressure Differentials

6.3.1 The commercial kitchen ventilation system shall be designed to establish pressure differentials to control odor migration and to control dust, dirt, and insects in accordance with the criteria in the following subsections.

6.3.1.1 The kitchen of a food-service facility shall be maintained under a negative pressure with respect to dining areas and adjacent nonfood areas. The maximum negative pressure shall not exceed 5.0 Pa.

6.3.1.2 A freestanding food-service facility (i.e., a food-service facility that entirely occupies a single building) shall be maintained under a positive pressure with respect to outdoors.

Exception: Where migration of food odors to adjacent interior rooms within the same tenancy would not be objectionable. Display cooking under a hood located in the dining area is not considered a kitchen.

6.3.2 Where a food-service facility shares a wall with an adjacent non-food-service facility, such as a retail center or a shopping mall, the food-service facility shall be maintained under a negative pressure with respect to outdoors and the adjacent spaces.

Exceptions:

1. Where the separation between the food service facility and the adjacent interior room is sealed substantially airtight to prevent odor migration.
2. In shopping malls and other occupancies where a food-service facility is open to another tenancy or to the mall common area, the food-service facility shall be permitted to be under a negative pressure with respect to the non-food-service occupancy.

6.3.3 The pressure in any room in which a draft-hood vented appliance, such as a gas water heater, is located shall be maintained not less than 5.0 Pa below outdoor ambient pressure.

7. SYSTEM CONTROLS

7.1 Operating Controls

7.1.1 Replacement air systems shall be interlocked to ensure operation upon activation of the exhaust system.

7.1.2 Demand-Control Ventilation

7.1.2.1 The exhaust flow rate is permitted to be reduced during partial load cooking and when there is no cooking through the means of demand-control ventilation.

7.1.2.2 Exhaust rates shall maintain capture and containment of appliance flue gases and cooking effluent during full-load, partial, or idle operating conditions.

7.1.2.3 During periods of reduced exhaust airflow, replacement air shall be automatically controlled to maintain the building pressure differentials in accordance with Section 6.3.

Informative Note: Replacement air units may have minimum airflow requirements for safe or effective operation of heating and/or cooling/dehumidification functions. Demand-control ventilation systems' minimum airflow settings must not be set lower than the replacement air systems minimum operating airflow.

7.1.2.4 Demand-control ventilation systems shall be part of a listed hood, shall be listed for the purpose, or shall be engineered.

Fire Suppression

Exhaust systems serving grease-producing equipment must include a fire-extinguishing system unless listed grease removal devices are installed. Wet chemical systems with nozzles over cooking equipment, in the hood and at the duct collar downstream of hood are commonly used, per NFPA 17A. Water from wet-pipe sprinkler systems can be used, per NFPA 13.

3. WATER

Table 3.1 Common Pump Terms, Symbols, and Formulas

Term	Symbol	Units	Formula
Velocity	v	m/s	
Volume	V	m^3	
Flow rate	Q_v	m^3/s or L/s	
Pressure	p	kPa	
Density	ρ	kg/m^3	
Acceleration of gravity	g	9.807 m/s^2	
Speed	n	rpm or rad	
Specific gravity	SG	—	$= \dfrac{\text{Mass of liquid}}{\text{Mass of water}}$
Head	H	m	2.31 p/SG
Net positive suction head (NPSH)	H	m	
Efficiency (percent)			
Pump	η_p		
Electric motor	η_m		
Variable speed drive	η_v		
Equipment (constant-speed pumps)	η_e		$\eta_e = \eta_p \eta_m / 100$
Equipment (variable-speed pumps)	η_e		$\eta_e = 10^{-4} \eta_p \eta_m \eta_v$
Utilization	$\eta_{\boldsymbol{u}}$		
Q_D = design flow			$\eta_u = 100 \dfrac{Q_D H_D}{Q_A H_A}$
Q_A = actual flow			
H_D = design head			
H_A = actual head			
System Efficiency Index (decimal)			SEI = $10^{-4} \eta_\varepsilon \eta_{\boldsymbol{u}}$
Output power (pump)	P_o	kW	$Q_v \rho m/101$ (Q_v in L/s)
Shaft power	P_s	kW	$100 P_o / \eta_p$
Input power	P_i	kW	$100 P_s / \eta_m$

Table 3.2 Affinity Laws for Pumps

Impeller Diameter	Speed	Specific Gravity (SG)	To Correct for	Multiply by
Constant	Variable	Constant	Flow	$\left(\dfrac{\text{New Speed}}{\text{Old Speed}}\right)$
			Head	$\left(\dfrac{\text{New Speed}}{\text{Old Speed}}\right)^2$
			Power	$\left(\dfrac{\text{New Speed}}{\text{Old Speed}}\right)^3$
Variable	Constant	Constant	Flow	$\left(\dfrac{\text{New Diameter}}{\text{Old Diameter}}\right)$
			Head	$\left(\dfrac{\text{New Diameter}}{\text{Old Diameter}}\right)^2$
			Power	$\left(\dfrac{\text{New Diameter}}{\text{Old Diameter}}\right)^3$
Constant	Constant	Variable	Power	$\left(\dfrac{\text{New SG}}{\text{Old SG}}\right)$

$$\text{pump power, kW} = \frac{\text{L/s} \times \text{m head} \times \text{sp. gr.}}{101 \times \eta_p \times \eta_m}$$

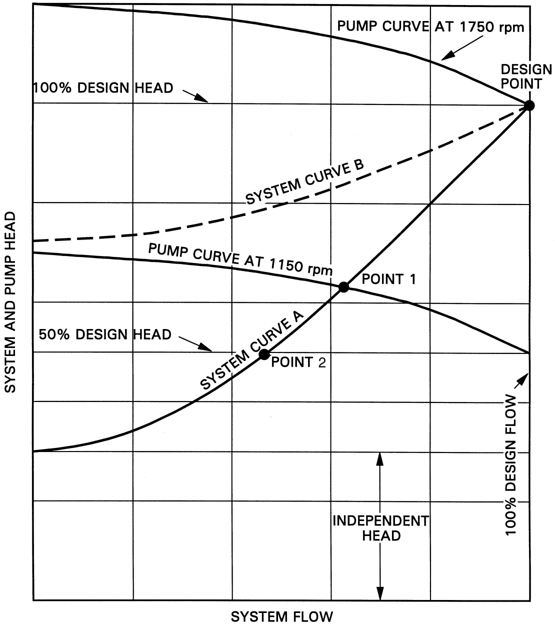


Figure 3.1 Pump Curves and System Curves

If the hydronic system has a system head curve as shown in curve A, the pump at 1150 rpm will operate at point 1, not at point 2, as would be predicted by the affinity laws alone. If the hydronic system has a system head curve like curve B of Figure 3.1, the pump at 1150 rpm will run at shutoff head and deliver no water. This demonstrates that the affinity laws should be used to develop new pump head/capacity curves, but not to predict performance with a particular hydronic system unless its system head curve is known.

Net Positive Suction Characteristics

Particular attention must be given to the pressure and temperature of the water as it enters the pump, especially in condenser towers, steam condensate returns, and steam boiler feeds.

The pressure in excess of that required to prevent vapor pockets from forming is the net positive suction head required (NPSHR). NPSHR is a characteristic of a given pump and varies with pump speed and flow. It is determined by the manufacturer and is included on the pump performance curve.

If the absolute pressure at the suction nozzle approaches the vapor pressure of the liquid, vapor pockets form in the impeller passages. The collapse of the vapor pockets (cavitation) is noisy and can be destructive to the pump impeller.

NPSHR is particularly important when a pump is operating with hot liquids or is applied to a circuit having a suction lift. The vapor pressure increases with water temperature and reduces the net positive suction head available (NPSHA). Each pump has its NPSHR, and the installation has its NPSHA, which is the total useful energy above the vapor pressure at the pump inlet.

$$\text{NPSHA} = p_p + p_z - p_{vpa} - p_f \tag{3.1}$$

where

p_p	=	absolute pressure on surface of liquid that enters pump, Pa
p_z	=	static elevation of liquid above center line of pump, Pa
p_{vpa}	=	absolute vapor pressure at pumping temperature, Pa
p_f	=	friction and head losses in suction piping, Pa

To determine the NPSHA in an existing installation, Equation 3.2 may be used (see Figure 3.2):

$$\text{NPSHA} = p_a + p_s + \frac{V^2\rho}{2} - p_{vpa} \tag{3.2}$$

where

p_a	=	atmospheric head for elevation of installation, Pa
p_s	=	head at inlet flange corrected to center line of pump (h_s is negative if below atmospheric pressure), Pa
$V^2\rho/2$	=	velocity head at point of measurement of h_s, Pa
ρ	=	density of fluid, kg/m^3

If the NPSHA is less than the pump's NPSHR, cavitation, noise, inadequate pumping, and mechanical problems will result. **For trouble-free design, the NPSHA must always be greater than the pump's NPSHR.** In closed hot- and chilled-water systems where sufficient system fill pressure is exerted on the pump suction, NPSHR is normally not a factor.

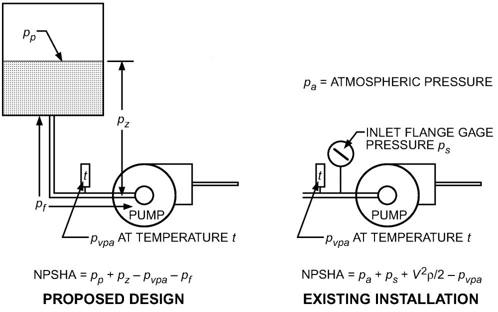


Figure 3.2 Net Positive Suction Head Available [2016S, Ch 44, Fig 33]

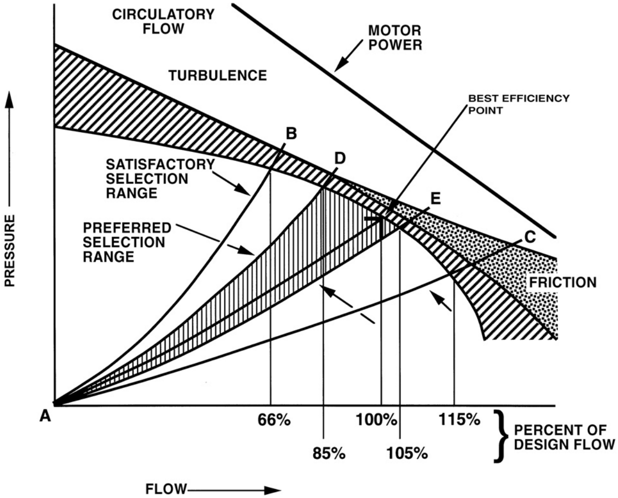


Figure 3.3 Pump Selection Regions [2016S, Ch 44, Fig 35]

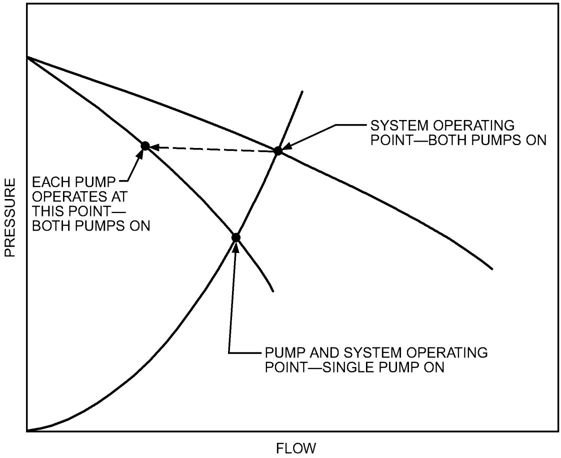


Figure 3.4 Operating Conditions for Parallel Operation [2016S, Ch 44, Fig 37]

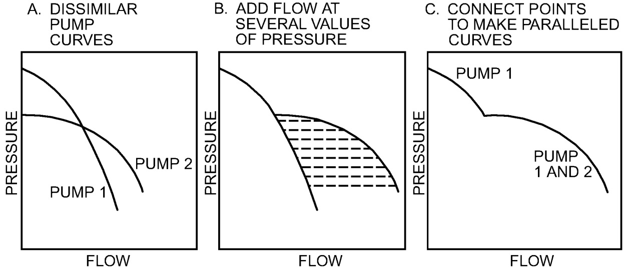


Figure 3.5 Construction of Curve for Dissimilar Parallel Pumps [2016S, Ch 44, Fig 38]

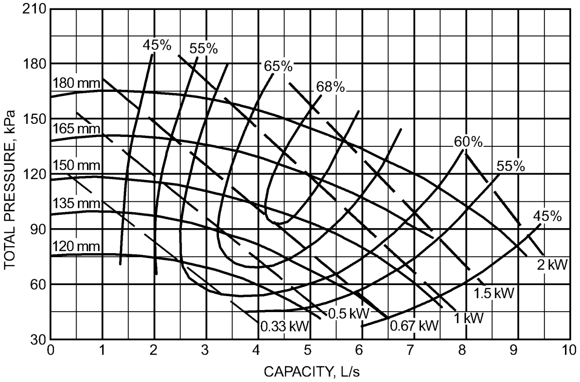


Figure 3.6 Typical Pump Curves (Curves Vary by Manufacturer) [2016S, Ch 44, Fig 13]

Table 3.3 Properties of Water—5°C to 95°C

Temperature, °C	Pressure, kPa	Density, kg/m^3	Total Heat above 0°C, kJ/kg	Specific Heat, kJ (kg·K)	Viscosity, mPa·s	Thermal Cond., mW/(m·K)
5	0.87	999.9	21.0	4.200	1519.1	570.5
10	1.23	999.7	42.0	4.188	1306.6	580.0
15	1.71	999.1	62.9	4.184	1138.2	589.3
20	2.34	998.2	83.8	4.183	1002.1	598.4
25	3.17	997.0	104.8	4.183	890.5	607.1
30	4.25	995.6	125.7	4.183	797.7	615.4
35	5.63	994.0	146.6	4.183	719.6	623.2
40	7.38	992.2	167.5	4.182	653.2	630.5
45	9.59	990.2	188.4	4.182	596.3	637.3
50	12.34	988.0	209.3	4.182	547.0	643.5
55	15.75	985.6	230.2	4.182	504.1	649.2
60	19.93	983.2	251.2	4.183	466.5	654.3
65	25.02	980.5	272.1	4.184	433.4	658.9
70	31.18	977.8	293.0	4.187	404.0	663.1
75	38.56	974.8	314.0	4.190	377.8	666.7
80	47.37	971.8	334.9	4.194	354.5	670.0
85	57.81	968.6	355.9	4.199	333.4	672.8
90	70.12	965.3	376.9	4.204	314.5	675.3
95	84.53	961.9	398.0	4.210	297.4	677.4

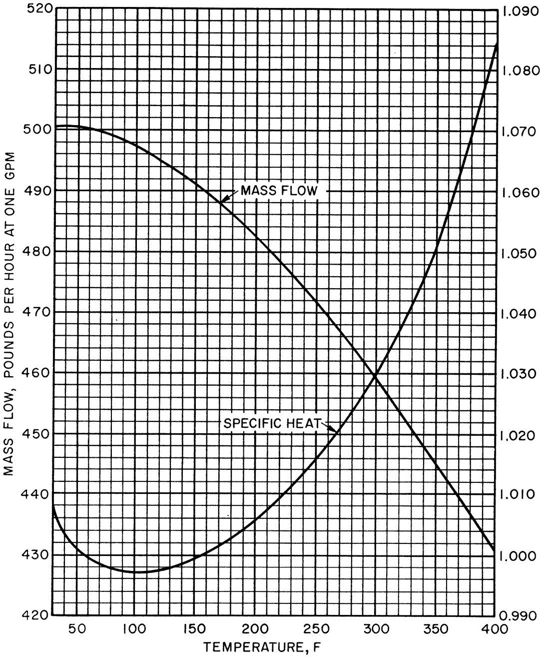


Figure 3.7 Mass Flow and Specific Heat of Water

Table 3.4 Freezing Points for Solutions of Ethylene Glycol and Propylene Glycol

Glycol, % by mass	Ethylene Glycol °C	Propylene Glycol °C
10	–3.2	–1.3
15	–5.4	–5.1
20	–7.8	–7.1
25	–10.7	–9.6
30	–14.1	–12.7
40	–22.3	–21.1
50	–33.8	–33.5
60	–48.3	–51.1

Ethylene glycol solutions are less viscous than propylene glycol solutions at the same concentration. Less toxic propylene glycol is preferred for applications involving possible human contact.

Table 3.5 Volume of Cylindrical Tank per Metre of Depth

Diameter, m	Volume, m^3	Diameter, m	Volume, m^3
0.1	0.0079	3.1	7.548
0.3	0.0707	303	8.553
0.5	0.1963	3.5	9.621
0.7	0.3848	3.7	10.75
0.9	0.6362	3.9	11.95
1.1	0.9503	4.1	13.20
1.3	1.327	4.3	14.52
1.5	1.767	4.5	15.90
1.7	2.270	4.7	17.35
1.9	2.835	4.9	18.86
2.1	3.464	5.1	20.43
2.3	4.155	5.3	22.06
2.5	4.909	5.5	23.76
2.7	5.726	5.7	25.52
2.9	6.605	5.9	27.34

Volume per metre of depth = $\pi(\text{Diameter}/2)^2$

Table 3.6 Quantities for Various Depths of Vertical Cylindrical Tanks in Horizontal Position

% Depth Filled	% of Capacity	% Depth Filled	% of Capacity	% Depth Filled	% of Capacity	% Depth Filled	% of Capacity
1	.20	26	20.73	51	51.27	76	81.50
3	.90	28	23.00	53	53.81	78	83.68
5	1.87	30	25.31	55	56.34	80	85.77
7	3.07	32	27.66	57	58.86	82	87.76
9	4.45	34	30.03	59	61.36	84	89.68
11	5.98	36	32.44	61	63.86	86	91.50
13	7.64	38	34.90	63	66.34	88	93.20
15	9.40	40	37.36	65	68.81	90	94.80
17	11.27	42	39.89	67	71.16	92	96.26
19	13.23	44	42.40	69	73.52	94	97.55
21	15.26	46	44.92	71	75.93	96	98.66
23	17.40	48	47.45	73	78.14	98	99.50
25	19.61	50	50.00	75	80.39	100	100.0

Table 3.7 Volume of Water in Standard Pipe and Tube

Nominal Pipe Size, mm	Schedule No.	Standard Steel Pipe Inside Diameter, mm	Standard Steel Pipe Volume, L/m	Type *L* Copper Tube Inside Diameter, mm	Type *L* Copper Tube Volume, L/m
(10)	—	—	—	(10.9)	(0.09)
(15)	40	(15.8)	(0.19)	(13.8)	(0.15)
(16)	—	—	—	(16.9)	(0.22)
(20)	40	(20.9)	(0.34)	(19.9)	(0.31)
(25)	40	(26.6)	(0.56)	(26.0)	(0.53)
(32)	40	(35.0)	(0.97)	(32.1)	(0.81)
(40)	40	(40.9)	(1.32)	(38.2)	(1.15)
(50)	40	(52.5)	(2.16)	(50.4)	(2.00)
(65)	40	(62.7)	(3.09)	(62.6)	(3.08)
(80)	40	(77.9)	(4.77)	(74.8)	(4.40)
(90)	40	(90.1)	(6.38)	(87.0)	(5.95)
(100)	40	(102.3)	(8.21)	(99.2)	(7.73)
(125)	40	(128.2)	(12.92)	(123.8)	(12.05)
(150)	40	(154.1)	(18.63)	(148.5)	(17.26)
(200)	30	(205.0)	(33.03)	(196.2)	(30.18)
(250)	30	(257.5)	(52.04)	(244.5)	(46.95)
(300)	30	(307.1)	(74.02)	(293.8)	(67.81)

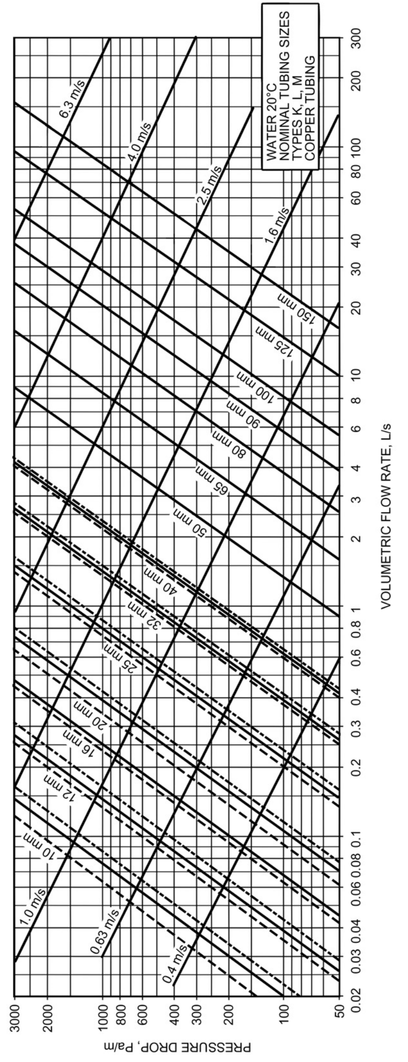


Figure 3.8 Friction Loss for Water in Copper Tubing (Types K, L, M) [2017F, Ch 22, Fig 15]

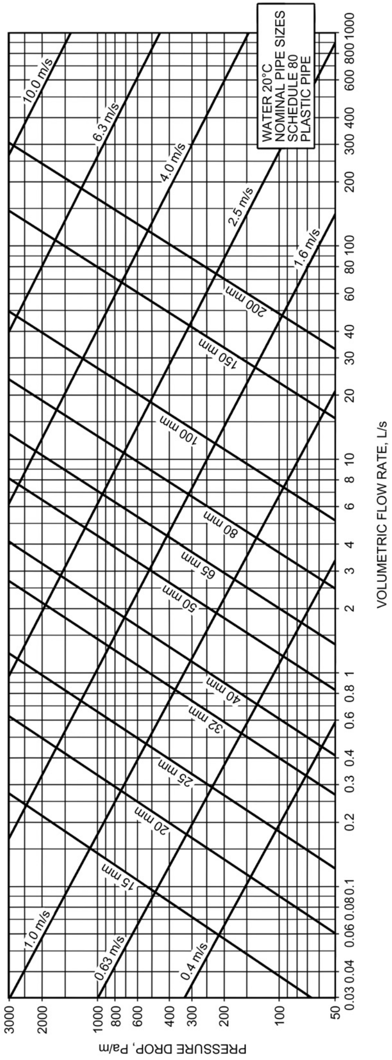


Figure 3.9 Friction Loss for Water in Plastic Pipe (Schedule 80) [2017F, Ch 22, Fig 16]

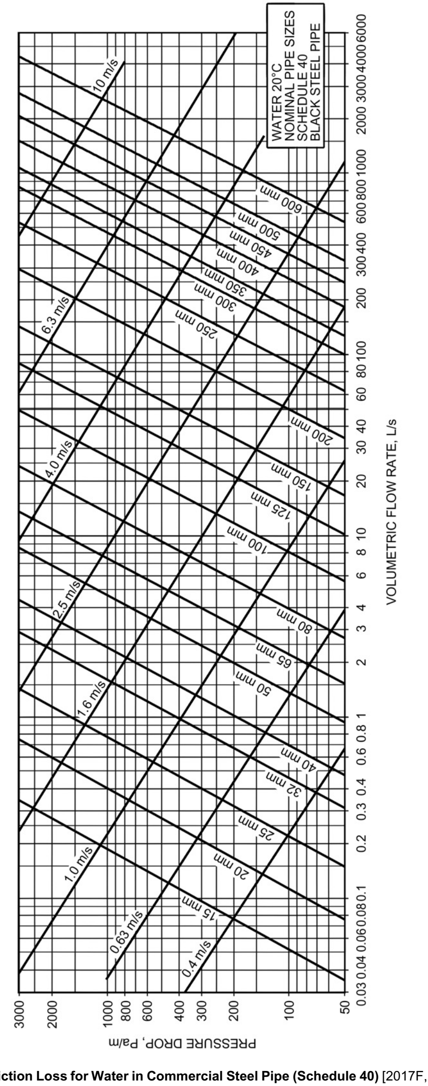


Figure 3.10 Friction Loss for Water in Commercial Steel Pipe (Schedule 40) [2017F, Ch 22, Fig 14]

Valve and Fitting Losses

Valves and fittings cause pressure losses greater than those caused by the pipe alone. One formulation expresses losses as

$$\Delta p = K\rho\left(\frac{V^2}{2}\right) \text{ or } \Delta h = K\left(\frac{V^2}{2g}\right) \tag{3.3}$$

where K = geometry- and size-dependent loss coefficient (see Tables 3.8 to 3.13).

ASHRAE research project RP-1193 found the data in Tables 3.8 to 3.13 giving K factors for Schedule 80 PVC 50, 100, 150, and 200 mm ells, reducers, expansions, and tees. In general, PVC fitting geometry varied much more from one manufacturer to another than steel fittings did.

Calculating Pressure Losses

The most common engineering design flow loss calculation selects a pipe size for the desired total flow rate and available or allowable pressure drop.

Because either formulation of fitting losses requires a known diameter, pipe size must be selected before calculating the detailed influence of fittings. A frequently used rule of thumb assumes that the design length of pipe is 50 to 100% longer than actual to account for fitting losses. After a pipe diameter has been selected on this basis, the influence of each fitting can be evaluated.

Table 3.8 *K* Factors: Threaded Pipe Fittings [2017F, Ch 22, Tbl 3]

Nominal Pipe Dia., mm	90° Ell Reg.	90° Ell Long	45° Ell	Return Bend	Tee-Line	Tee-Branch	Globe Valve	Gate Valve	Angle Valve	Swing Check Valve	Bell Mouth Inlet	Square Inlet	Projected Inlet
10	2.5	—	0.38	2.5	0.90	2.7	20	0.40	—	8.0	0.05	0.5	1.0
15	2.1	—	0.37	2.1	0.90	2.4	14	0.33	—	5.5	0.05	0.5	1.0
20	1.7	0.92	0.35	1.7	0.90	2.1	10	0.28	6.1	3.7	0.05	0.5	1.0
25	1.5	0.78	0.34	1.5	0.90	1.8	9	0.24	4.6	3.0	0.05	0.5	1.0
32	1.3	0.65	0.33	1.3	0.90	1.7	8.5	0.22	3.6	2.7	0.05	0.5	1.0
40	1.2	0.54	0.32	1.2	0.90	1.6	8	0.19	2.9	2.5	0.05	0.5	1.0
50	1.0	0.42	0.31	1.0	0.90	1.4	7	0.17	2.1	2.3	0.05	0.5	1.0
65	0.85	0.35	0.30	0.85	0.90	1.3	6.5	0.16	1.6	2.2	0.05	0.5	1.0
80	0.80	0.31	0.29	0.80	0.90	1.2	6	0.14	1.3	2.1	0.05	0.5	1.0
100	0.70	0.24	0.28	0.70	0.90	1.1	5.7	0.12	1.0	2.0	0.05	0.5	1.0

Source: *Engineering Data Book* (Hydraulic Institute 1990).

Table 3.9 *K* Factors: Flanged Welded Pipe Fittings [2017F, Ch 22, Tbl 4]

Nominal Pipe Dia., mm	90° Ell Reg.	90° Ell Long	45° Ell Long	Return Bend Standard	Return Bend Long-Radius	Tee-Line	Tee-Branch	Glove Valve	Gate Valve	Angle Valve	Swing Check Valve
25	0.43	0.41	0.22	0.43	0.43	0.26	1.0	13	—	4.8	2.0
32	0.41	0.37	0.22	0.41	0.38	0.25	0.95	12	—	3.7	2.0
40	0.40	0.35	0.21	0.40	0.35	0.23	0.90	10	—	3.0	2.0
50	0.38	0.30	0.20	0.38	0.30	0.20	0.84	9	0.34	2.5	2.0
65	0.35	0.28	0.19	0.35	0.27	0.18	0.79	8	0.27	2.3	2.0
80	0.34	0.25	0.18	0.34	0.25	0.17	0.76	7	0.22	2.2	2.0
100	0.31	0.22	0.18	0.31	0.22	0.15	0.70	6.5	0.16	2.1	2.0
150	0.29	0.18	0.17	0.29	0.18	0.12	0.62	6	0.10	2.1	2.0
200	0.27	0.16	0.17	0.27	0.15	0.10	0.58	5.7	0.08	2.1	2.0
250	0.25	0.14	0.16	0.25	0.14	0.09	0.53	5.7	0.06	2.1	2.0
300	0.24	0.13	0.16	0.24	0.13	0.08	0.50	5.7	0.05	2.1	2.0

Source: *Engineering Data Book* (Hydraulic Institute 1990).

Table 3.10 Summary of *K* Factors for Reducers and Expansions [2017F, Ch 22, Tbl 6]

		ASHRAE Research[a,b]		
		1.2 m/s	2.4 m/s	3.6 m/s
Reducer	(50 by 40 mm) thread	0.53	0.28	0.20
	(100 by 80 mm) weld	0.23	0.14	0.10
	(150 by 100 mm) weld	0.62	0.54	0.53
	(200 by 150 mm) weld	0.31	0.28	0.26
	(250 by 200 mm) weld	0.16	0.14	0.14
	(300 by 250 mm) weld	0.14	0.14	0.14
	(400 by 300 mm) weld	0.17	0.16	0.17
	(500 by 400 mm) weld	0.16	0.13	0.13
	(600 by 500 mm) weld	0.053	0.053	0.055
Expansion	(40 by 50 mm) thread	0.16	0.13	0.02
	(80 by 100 mm) weld	0.11	0.11	0.11
	(100 by 150 mm) weld	0.28	0.28	0.29
	(150 by 200 mm) weld	0.15	0.12	0.11
	(200 by 250 mm) weld	0.11	0.09	0.08
	(250 by 300 mm) weld	0.11	0.11	0.11
	(300 by 400 mm) weld	0.073	0.076	0.073
	(400 by 500 mm) weld	0.024	0.021	0.022
	(500 by 600 mm) weld	0.020	0.023	0.020

Source: Rahmeyer (2003a). [a]Rahmeyer (1999a, 2002a). [b]Ding et al. (2005)

Table 3.11 Summary of *K* Factors for Pipe Tees [2017F, Ch 22, Tbl 7]

		ASHRAE Research[a,b]		
		1.2 m/s	2.4 m/s	3.6 m/s
50 mm thread tee,	100% branch	0.93	—	—
	100% line (flow-through)	0.19	—	—
	100% mix	1.19	—	
100 mm weld tee,	100% branch	—	0.57	—
	100% line (flow-through)	—	0.06	—
	100% mix	—	0.49	—
150 mm weld tee,	100% branch	—	0.56	—
	100% line (flow-through)	—	0.12	—
	100% mix	—	0.88	—
200 mm weld tee,	100% branch	—	0.53	—
	100% line (flow-through)	—	0.08	—
	100% mix	—	0.70	—
250 mm weld tee,	100% branch	—	0.52	—
	100% line (flow-through)	—	0.06	—
	100% mix	—	0.77	—
300 mm weld tee,	100% branch	0.70	0.63	0.62
	100% line (flow-through)	0.062	0.091	0.096
	100% mix	0.88	0.72	0.72
400 mm weld tee,	100% branch	0.54	0.55	0.54
	100% line (flow-through)	0.032	0.028	0.028
	100% mix	0.74	0.74	0.76

[a]Rahmeyer (1999b, 2002b). [b]Ding et al. (2005).

Table 3.12 Test Summary for Loss Coefficients *K* and Equivalent Loss Lengths [2017F, Ch 22, Tbl 8]

Schedule 80 PVC Fitting		*K*	*L*, m
Injected molded elbow,	50 mm	0.91 to 1.00	2.6 to 2.8
	100 mm	0.86 to 0.91	5.6 to 5.9
	150 mm	0.76 to 0.91	8.0 to 9.5
	200 mm	0.68 to 0.87	10.0 to 12.8
200 mm fabricated elbow, Type I, components		0.40 to 0.42	5.9 to 6.2
Type II, mitered		0.073 to 0.76	10.8 to 11.2
150 by 100 mm injected molded reducer		0.12 to 0.59	1.2 to 6.2
Bushing type		0.49 to 0.59	5.2 to 6.2
200 by 150 mm injected molded reducer		0.13 to 0.63	1.9 to 9.3
Bushing type		0.48 to 0.68	7.1 to 10.0
Gradual reducer type		0.21	3.1
100 by 150 mm injected molded expansion		0.069 to 1.19	0.46 to 7.7
Bushing type		0.069 to 1.14	0.46 to 7.4
150 by 200 mm injected molded expansion		0.95 to 0.96	10.0 to 10.1
Bushing type		0.94 to 0.95	9.9 to 10.0
Gradual reducer type		0.99	10.4

Table 3.13 Test Summary for Loss Coefficients *K* of PVC Tees [2017F, Ch 22, Tbl 9]

Branching		
Schedule 80 PVC Fitting	$K_{1\text{-}2}$	$K_{1\text{-}3}$
50 mm injection molded branching tee, 100% line flow	0.13 to 0.26	—
50/50 flow	0 to 0.12	0.74 to 1.02
100% branch flow	—	0.98 to 1.39
100 mm injection molded branching tee, 100% line flow	0.07 to 0.22	—
50/50 flow	0.03 to 0.13	0.74 to 0.82
100% branch flow	—	0.97 to 1.12
150 mm injection molded branching tee, 100% line flow	0.01 to 0.14	—
50/50 flow	0.06 to 0.11	0.70 to 0.84
100% branch flow	—	0.95 to 1.15
150 mm fabricated branching tee, 100% line flow	0.21 to 0.22	—
50/50 flow	0.04 to 0.09	1.29 to 1.40
100% branch flow	—	1.74 to 1.88
200 mm injection molded branching tee, 100% line flow	0.04 to 0.09	—
50/50 flow	0.04 to 0.07	0.64 to 0.75
100% branch flow	—	0.85 to 0.96
200 mm fabricated branching tee, 100% line flow	0.09 to 0.16	—
50/50 flow	0.08 to 0.13	1.07 to 1.16
100% branch flow	—	1.40 to 1.62
Mixing		
PVC Fitting	$K_{1\text{-}2}$	$K_{3\text{-}2}$
50 mm injection molded mixing tee, 100% line flow	0.12 to 0.25	—
50/50 flow	1.22 to 1.19	0.89 to 1.88
100% mix flow	—	0.89 to 1.54
100 mm injection molded mixing tee, 100% line flow	0.07 to 0.18	—
50/50 flow	1.19 to 1.88	0.98 to 1.88
100% mix flow	—	0.88 to 1.02
150 mm injection molded mixing tee, 100% line flow	0.06 to 0.14	—
50/50 flow	1.26 to 1.80	1.02 to 1.60
100% mix flow	—	0.90 to 1.07
150 mm fabricated mixing tee, 100% line flow	0.19 to 0.21	—
50/50 flow	2.94 to 3.32	2.57 to 3.17
100% mix flow	—	1.72 to 1.98
200 mm injection molded mixing tee, 100% line flow	0.04 to 0.09	—
50/50 flow	1.10 to 1.60	0.96 to 1.32
100% mix flow	—	0.81 to 0.93
200 mm fabricated mixing tee, 100% line flow	0.13 to 0.70	—
50/50 flow	2.36 to 10.62	2.02 to 2.67
100% mix flow	—	1.34 to 1.53

Coefficients based on average velocity of 2.43 m/s. Range of values varies with fitting manufacturers. Line or straight flow is Q_2/Q_1 = 100%. Branch flow is Q_2/Q_1 = 0%.

4. STEAM

Table 4.1 Properties of Saturated Steam[a]

Absolute Pressure p, kPa	Temperature t_s, °C	Specific Enthalpy, kJ/kg In Saturated Liquid h_f	Latent Heat of Evaporation h_{fg}	In Saturated Vapor h_g	Spec. Vol. v, m^3/kg
1	6.98	29.3	2484.3	2513.6	129.205
2	17.51	73.5	2459.5	2533.0	67.010
4	28.98	121.4	2432.4	2553.9	34.805
6	36.18	151.5	2415.3	2566.8	23.742
8	41.53	173.9	2404.5	2576.4	18.104
10	45.83	191.8	2392.2	2584.1	14.673
20	60.09	251.5	2357.7	2609.1	7.648
30	69.13	289.3	2335.4	2624.8	5.228
40	75.89	317.7	2318.6	2636.3	3.992
50	81.35	340.6	2304.9	2645.4	3.239
60	85.95	359.9	2293.2	2653.1	2.731
70	89.96	376.8	2282.9	2659.7	2.364
80	93.51	391.7	2273.7	2665.4	2.087
90	96.71	405.2	2265.4	2670.6	1.869
100	99.63	417.5	2257.7	2675.2	1.694
110	102.32	428.8	2250.6	2679.5	1.549
120	104.81	439.3	2244.0	2683.3	1.428
130	107.13	449.2	2237.8	2686.9	1.325
140	109.32	458.4	2231.9	2690.3	1.237
150	11.37	467.5	2226.3	2693.4	1.159
160	113.32	475.4	2221.0	2696.4	1.091
170	115.17	483.2	2215.9	2699.1	1.031
180	116.93	490.7	2211.1	2701.8	0.977
190	118.62	497.9	2206.4	2704.2	0.929
200	120.23	504.7	2201.9	2706.6	0.886
210	121.78	511.3	2197.6	2708.9	0.846
220	123.27	517.6	2193.4	2711.0	0.810
230	124.71	523.7	2189.3	2713.1	0.777
240	126.09	529.6	2185.4	2715.0	0.747
250	127.43	535.4	2181.6	2716.9	0.719
260	128.73	540.9	2177.8	2718.7	0.693
270	129.99	546.2	2174.2	2720.5	0.669
280	131.21	551.5	2170.7	2722.2	0.646
290	132.39	556.5	2167.3	2723.8	0.625
300	133.54	561.4	2163.9	2735.4	0.606
310	134.66	566.2	2160.6	2726.9	0.587
320	135.76	570.9	2157.4	2728.4	0.570
330	136.82	575.5	2154.3	2729.8	0.554
340	137.86	579.9	2151.2	2731.1	0.539
350	138.88	584.3	2148.2	2732.5	0.524
360	139.87	588.5	2145.2	2733.8	0.510
370	140.84	592.7	2142.3	2735.0	0.497
380	141.79	596.8	2139.5	2736.3	0.485
390	142.72	600.8	2136.7	2737.5	0.473
400	143.63	604.7	2133.9	2738.6	0.462
410	144.52	608.5	2131.2	2739.8	0.452

Table 4.1 Properties of Saturated Steam[a] *(Continued)*

Absolute Pressure p, kPa	Temperature t_s, °C	Specific Enthalpy, kJ/kg In Saturated Liquid h_f	Latent Heat of Evaporation h_{fg}	In Saturated Vapor h_g	Spec. Vol. v, m^3/kg
420	145.39	612.3	2138.6	2740.9	0.442
430	146.25	616.0	2125.9	2741.9	0.432
440	147.09	619.6	2123.4	2743.0	0.423
450	147.92	623.2	2120.8	2744.0	0.414
460	148.73	626.7	2118.2	2745.0	0.405
470	149.53	630.1	2115.8	2746.0	0.397
480	150.31	633.5	2113.4	2746.9	0.389
490	151.09	636.8	2111.0	2747.8	0.382
500	151.85	640.1	2108.6	2748.7	0.375
520	153.33	646.5	2104.0	2750.5	0.361
540	154.77	652.8	2099.4	2752.2	0.349
560	156.16	658.8	2095.0	2753.8	0.337
580	157.52	664.7	2090.7	2755.4	0.326
600	158.84	670.4	2086.4	2756.8	0.316
620	160.12	676.0	2082.3	2758.3	0.306
640	161.38	681.5	2078.2	2759.9	0.297
660	162.60	686.8	2074.2	2761.0	0.288
680	163.79	692.0	2070.3	2762.3	0.280
700	164.96	697.1	2066.4	2763.5	0.273
720	166.10	702.0	2062.7	2764.7	0.266
740	167.21	706.9	2058.9	2765.8	0.259
760	168.30	711.7	2055.3	2767.0	0.252
780	169.37	716.4	2051.7	2768.0	0.246
800	170.41	720.9	2048.2	2769.1	0.240
820	171.44	725.4	2044.7	2770.1	0.235
840	172.45	729.8	2041.2	2771.1	0.229
860	173.43	734.2	2037.8	2772.0	0.224
880	174.40	738.4	2034.5	2772.9	0.220
900	175.36	742.6	2031.2	2773.8	0.215
920	176.29	746.8	2028.0	2774.7	0.210
940	177.21	750.8	2024.7	2775.6	0.206
960	178.12	754.8	2021.6	2776.4	0.202
980	179.01	758.7	2018.4	2777.2	0.198
1000	179.88	762.6	2015.3	2777.9	0.194
1100	184.06	781.1	2000.4	2781.5	0.177
1200	187.96	798.4	1986.2	2784.6	0.163
1300	191.60	814.7	1972.6	2787.3	0.151
1400	195.04	830.0	1959.6	2789.7	0.141
1500	198.28	844.6	1947.1	2791.8	0.132
1600	201.37	858.5	1935.1	2793.6	0.124
1700	204.30	871.8	1923.4	2795.2	0.117
1800	207.10	884.5	1912.1	2796.6	0.110
1900	209.79	896.8	1901.1	2797.8	0.105
2000	212.37	908.6	1890.4	2798.9	0.100

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Table 4.2 Flow Rate of Steam in Schedule 40 Pipe [2017F, Ch 22, Tbl 32]

Nominal Pipe Size, mm	Pressure Drop, Pa/m													
	14 Pa/m		28 Pa/m		58 Pa/m		113 Pa/m		170 Pa/m		225 Pa/m		450 Pa/m	
	Sat. Press., kPa		Sat. Press., kPa		Sat. Press., kPa		Sat. Press., kPa		Sat. Press., kPa		Sat. Press., kPa		Sat. Press., kPa	
	25	85	25	85	25	85	25	85	25	85	25	85	25	85
20	1.1	1.4	1.8	2.0	2.5	3.0	3.7	4.4	4.5	5.4	5.3	6.3	7.6	9.2
25	2.1	2.6	3.3	3.9	4.7	5.8	6.8	8.3	8.6	10	10	12	14	17
32	4.5	5.7	6.7	8.3	9.8	12	14	17	18	21	20	25	29	35
40	7.1	8.8	11	13	15	19	22	26	27	33	31	38	45	54
50	14	17	20	24	29	36	42	52	53	64	60	74	89	107
65	22	27	33	39	48	58	68	83	86	103	98	120	145	173
80	40	48	59	69	83	102	121	146	150	180	174	210	246	302
90	58	69	84	101	125	153	178	214	219	265	252	305	372	435
100	81	101	120	146	178	213	249	302	309	378	363	436	529	617
125	151	180	212	265	307	378	450	536	552	662	643	769	945	1 080
150	242	290	355	422	499	611	718	857	882	1 080	1 060	1 260	1 500	1 790
200	491	605	702	882	1 020	1 260	1 440	1 800	1 830	2 230	2 080	2 580	3 020	3 720
250	907	1 110	1 290	1 590	1 890	2 290	2 650	3 280	3 300	4 030	3 780	4 660	5 380	6 550
300	1 440	1 730	2 080	2 460	2 950	3 580	4 160	5 040	5 170	6 240	6 050	7 250	8 540	10 200

Notes:
1. Flow rate is in g/s at initial saturation pressures of 25 and 85 kPa (gage). Flow is based on Moody friction factor, where the flow of condensate does not inhibit the flow of steam.
2. The flow rates at 25 kPa cover saturated pressure from 7 to 41 kPa, and the rates at 85 kPa cover saturated pressure from 55 to 110 kPa with an error not exceeding 8%.

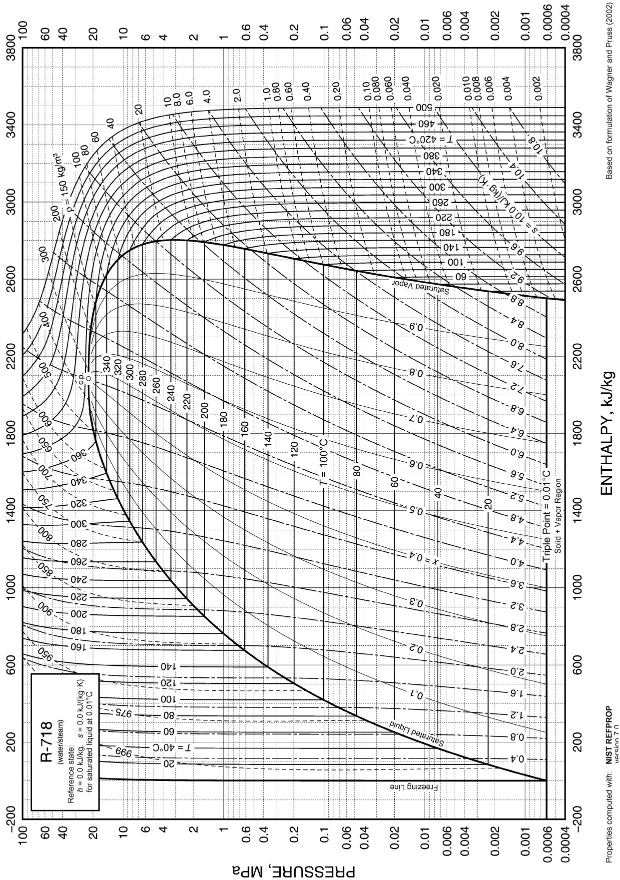


Figure 4.1 Pressure-Enthalpy Diagram for Refrigerant 718 (Water/Steam) [2017F, Ch 30, Fig 20]

Table 4.3 Steam Pipe Capacities for Low-Pressure Systems

[2017F, Ch 22, Tbl 33]

Nominal Pipe Size, mm	Capacity, kg/h				
	Two-Pipe System		Supply Risers Up-Feed	One-Pipe System	
	Condensate Flowing Against Steam			Radiator Valves and Vertical Connections	Radiator and Riser Runouts
	Vertical	Horizontal			
A	B[a]	C[c]	D[b]	E	F[c]
20	4	3	3	-	3
25	6	6	5	3	3
32	14	12	9	7	7
40	22	19	17	10	7
50	44	42	33	19	10
65	72	60	53	-	19
80	128	91	91	-	29
90	176	131	130	-	54
100	232	193	172	-	84
125	476	357	-	-	126
150	816	635	-	-	247
200	1700	1360	-	-	-
250	3180	2590	-	-	-
300	5220	4310	-	-	-
400	9980	8620	-	-	-

Note: Steam at an average pressure of 7kPa above atmospheric is used as a basis of calculating capacities.

[a]Do not use Column B for pressure drops of less than 13 Pa/m of equivalent run.

[b]Do not use Column D for pressure drops of less than 9 Pa/m of equivalent run, except on sizes 80 mm and over.

[c]Pitch of horizontal runouts to risers and radiators should be not less than 40 mm/m. Where this pitch cannot be obtained, runouts over 2.5 m in length should be one pipe size larger than called for in this table.

Table 4.4 Return Main and Riser Capacities for Low-Pressure Systems, kg/h [2017F, Ch 22, Tbl 34]

	Pipe Size, mm	7 Pa/m			9 Pa/m			14 Pa/m			28 Pa/m			57 Pa/m			113 Pa/m		
		Wet	Dry	Vac.	Wet	Dry	Vac.	Wet	Dry	Vac.	Wet	Dry	Vac.	Wet	Dry	Vac.	Wet	Dry	Vac.
	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
Return Main	20						19			45			64			91			128
	25	57	28		66	32	65	79	36	79	113	47	113	159	52	159			224
	32	97	59		112	68	111	136	76	136	193	98	193	272	109	272			385
	40	153	93		178	107	176	215	120	215	306	154	306	431	171	431			608
	50	318	213		367	243	370	454	261	454	635	336	644	907	374	907			1280
	65	535	345		717	394	616	762	431	762	1070	558	1080	1520	617	1520			2150
	80	853	662		966	708	989	1220	794	1220	1700	1020	1720	2430	1130	2430			3430
	90	1250	894		1500	998	1400	1810	1130	1810	2490	1470	2580	3630	1620	3630			5130
	100	1760	1330		2080	1520	2040	2490	1700	2490	3520	2190	3540	4990	2440	4990			7030
	125						3570			4390			6210			8800			12400
	150						5720			7030			9980			14100			19900
Riser	20		22			22	65		22	79		22	113		22	159			224
	25		51			51	111		51	136		51	193		51	272			385
	32		112			112	176		112	215		112	306		112	431			608
	40		170			170	370		170	454		170	644		170	907			1280
	50		340			340	616		340	762		340	1080		340	1520			2150
	65						989			1220			1720			2430			3430
	80						1470			1810			2580			3630			5130
	70						2030			2490			3540			4990			7030
	100						3570			4390			6210			8800			12400
	125						5720			7030			9980			14100			19900

5. PIPING

Table 5.1 Steel Pipe Data [2017F, Ch 22, Tbl 16]

U.S. Nominal Size, in.	Nominal Size, mm	Schedule[a]	Wall Thickness t, mm	Inside Diameter d, mm	Surface Area		Cross Section		Mass		Working Pressure[c] ASTM A53 B to 200°C		
					Outside, m^2/m	Inside, m^2/m	Metal Area, mm^2	Flow Area, mm^2	Pipe, kg/m	Water, kg/m	Mfr. Process	Joint Type[b]	kPa (gage)
1/4	8	40 ST	2.24	9.25	0.043	0.029	80.6	67.1	0.631	0.067	CW	T	1296
		80 XS	3.02	7.67	0.043	0.024	101.5	46.2	0.796	0.046	CW	T	6006
3/8	10	40 ST	2.31	12.52	0.054	0.039	107.7	123.2	0.844	0.123	CW	T	1400
		80 XS	3.20	10.74	0.054	0.034	140.2	90.7	1.098	0.091	CW	T	5654
1/2	15	40 ST	2.77	15.80	0.067	0.050	161.5	196.0	1.265	0.196	CW	T	1476
		80 XS	3.73	13.87	0.067	0.044	206.5	151.1	1.618	0.151	CW	T	5192
3/4	20	40 ST	2.87	20.93	0.084	0.066	214.6	344.0	1.68	0.344	CW	T	1496
		80 XS	3.91	18.85	0.084	0.059	279.7	279.0	2.19	0.279	CW	T	4695
1	25	40 ST	3.38	26.64	0.105	0.084	318.6	557.6	2.50	0.558	CW	T	1558
		80 XS	4.55	24.31	0.105	0.076	412.1	464.1	3.23	0.464	CW	T	4427
1 1/4	32	40 ST	3.56	35.05	0.132	0.110	431.3	965.0	3.38	0.965	CW	T	1579
		80 XS	4.85	32.46	0.132	0.102	568.7	827.6	4.45	0.828	CW	T	4096
1 1/2	40	40 ST	3.68	40.89	0.152	0.128	515.5	1 313	4.05	1.313	CW	T	1593
		80 XS	5.08	38.10	0.152	0.120	689.0	1 140	5.40	1.140	CW	T	3972
2	50	40 ST	3.91	52.50	0.190	0.165	690.3	2 165	5.43	2.165	CW	T	1586
		80 XS	5.54	49.25	0.190	0.155	953	1 905	7.47	1.905	CW	T	3799
2 1/2	65	40 ST	5.16	62.71	0.229	0.197	1 099	3 089	8.62	3.089	CW	W	3675
		80 XS	7.01	59.00	0.229	0.185	1 454	2 734	11.40	2.734	CW	W	5757

Table 5.1 Steel Pipe Data [2017F, Ch 22, Tbl 16] ***(Continued)***

U.S. Nominal Size, in.	Nominal Size, mm	Schedule[a]	Wall Thickness t, mm	Inside Diameter d, mm	Surface Area		Cross Section		Mass		Working Pressure[c] ASTM A53 B to 200°C		
					Outside, m^2/m	Inside, m^2/m	Metal Area, mm^2	Flow Area, mm^2	Pipe, kg/m	Water, kg/m	Mfr. Process	Joint Type[b]	kPa (gage)
3	80	40 ST	5.49	77.93	0.279	0.245	1 438	4 769	11.27	4.769	CW	W	3323
		80 XS	7.62	73.66	0.279	0.231	1 946	4 261	15.25	4.261	CW	W	5288
4	100	40 ST	6.02	102.26	0.359	0.321	2 048	8 213	16.04	8.213	CW	W	2965
		80 XS	8.56	97.18	0.359	0.305	2 844	7 417	22.28	7.417	CW	W	4792
6	150	40 ST	7.11	154.05	0.529	0.484	3 601	18 639	28.22	18.64	ERW	W	4799
		80 XS	10.97	146.33	0.529	0.460	5 423	16 817	42.49	16.82	ERW	W	8336
8	200	30	7.04	205.0	0.688	0.644	4 687	33 000	36.73	33.01	ERW	W	3627
		40 ST	8.18	202.7	0.688	0.637	5 419	32 280	42.46	32.28	ERW	W	4433
		80 XS	12.70	193.7	0.688	0.608	8 234	29 460	64.51	29.46	ERW	W	7626
10	250	30	7.80	257.5	0.858	0.809	6 498	52 060	50.91	52.06	ERW	W	3344
		40 ST	9.27	254.5	0.858	0.800	7 683	50 870	60.20	50.87	ERW	W	4178
		XS	12.70	247.7	0.858	0.778	10 388	48 170	81.39	48.17	ERW	W	6116
		80	15.06	242.9	0.858	0.763	12 208	46 350	95.66	46.35	ERW	W	7453
12	300	30	8.38	307.1	1.017	0.965	8 307	74 060	65.09	74.06	ERW	W	3096
		ST	9.53	304.8	1.017	0.958	9 406	72 970	73.70	72.97	ERW	W	3641
		40	10.31	303.2	1.017	0.953	10 158	72 190	79.59	72.21	ERW	W	4020
		XS	12.70	298.5	1.017	0.938	12 414	69 940	97.28	69.96	ERW	W	5157
		80	17.45	289.0	1.017	0.908	16 797	65 550	131.62	65.57	ERW	W	7419

Table 5.1 Steel Pipe Data [2017F, Ch 22, Tbl 16] ***(Continued)***

U.S. Nominal Size, in.	Nominal Size, mm	Schedule[a]	Wall Thickness t, mm	Inside Diameter d, mm	Surface Area		Cross Section		Mass		Working Pressure[c] ASTM A53 B to 200°C		
					Outside, m^2/m	Inside, m^2/m	Metal Area, mm^2	Flow Area, mm^2	Pipe, kg/m	Water, kg/m	Mfr. Process	Joint Type[b]	kPa (gage)
14	350	30 ST	9.53	336.6	1.117	1.057	10 356	88 970	81.15	88.96	ERW	W	3316
		40	11.10	333.4	1.117	1.047	12 013	87 290	94.13	87.30	ERW	W	3999
		XS	12.70	330.2	1.117	1.037	13 681	85 610	107.21	85.63	ERW	W	4695
		80	19.05	317.5	1.117	0.997	20 142	79 160	157.82	79.17	ERW	W	7453
16	400	30 ST	9.53	387.4	1.277	1.217	11 876	117 800	93.06	117.8	ERW	W	2903
		40 XS	12.70	381.0	1.277	1.197	15 708	114 000	123.09	114.0	ERW	W	4109
18	450	ST	9.53	438.2	1.436	1.376	13 396	150 800	104.98	150.8	ERW	W	2579
		30	11.10	435.0	1.436	1.367	15 556	148 600	121.90	148.6	ERW	W	3110
		XS	12.70	431.8	1.436	1.357	17 735	146 450	138.97	146.4	ERW	W	3654
		40	14.27	428.7	1.436	1.347	19 863	144 300	155.65	144.3	ERW	W	4185
20	500	20 ST	9.53	489.0	1.596	1.536	14 916	187 700	116.88	187.4	ERW	W	2324
		30 XS	12.70	482.6	1.596	1.516	19 762	182 900	154.85	182.9	ERW	W	3289
		40	15.06	477.9	1.596	1.501	23 325	179 400	182.78	179.4	ERW	W	4006

[a]Numbers are schedule numbers per ASME Standard B36.10M; ST = Standard; XS = Extra Strong.
[b]T = Thread; W = Weld.
[c]Working pressures were calculated per ASME B31.9 using furnace butt-weld (continuous weld, CW) pipe through 100 mm and electric resistance weld (ERW) thereafter. The allowance A has been taken as (1)12.5% of t for mill tolerance on pipe wall thickness, *plus*
(2)An arbitrary corrosion allowance of 0.64 mm for pipe sizes through NPS 2 and 1.65 mm from NPS 2 1/2 through 20, *plus*
(3)A thread cutting allowance for sizes through NPS 2.
Because the pipe wall thickness of threaded standard pipe is so small after deducting allowance A, the mechanical strength of the pipe is impaired. It is good practice to limit standard threaded pipe pressure to 620 kPa (gage) for steam and 860 kPa (gage) for water.

Table 5.2 Copper Tube Data [2017F, Ch 22, Tbl 17]

U.S. Nominal Size, in.	Type	Wall Thickness t, mm	Diameter		Surface Area		Cross Section		Mass		Working Pressure[a,b,c] ASTM B88 to 120°C MPa (gage)	
			Outside D, mm	Inside d, mm	Outside, m^2/m	Inside, m^2/m	Metal Area, mm^2	Flow Area, mm^2	Tube, kg/m	Water, kg/m	Annealed	Drawn
1/4	K	0.89	9.53	7.75	0.030	0.0244	24	47	0.216	0.047	5.868	11.004
	L	0.76	9.53	8.00	0.030	0.0250	21	50	0.188	0.050	5.033	9.432
3/8	K	1.24	12.70	10.21	0.040	0.0320	45	82	0.400	0.082	6.164	11.556
	L	0.89	12.70	10.92	0.040	0.0344	33	94	0.295	0.094	4.399	8.253
	M	0.64	12.70	11.43	0.040	0.0360	24	103	0.216	0.103	3.144	5.895
1/2	K	1.24	15.88	13.39	0.050	0.0421	57	141	0.512	0.141	4.930	9.246
	L	1.02	15.88	13.84	0.050	0.0436	48	151	0.424	0.151	4.027	7.543
	M	0.71	15.88	14.45	0.050	0.0454	34	164	0.302	0.164	2.820	5.282
5/8	K	1.24	19.05	16.56	0.060	0.0521	70	215	0.622	0.215	4.109	7.702
	L	1.07	19.05	16.92	0.060	0.0530	60	225	0.539	0.225	3.523	6.605
3/4	K	1.65	22.23	18.92	0.070	0.0594	106	281	0.954	0.281	4.668	8.757
	L	1.14	22.23	19.94	0.070	0.0628	75	312	0.677	0.312	3.234	6.061
	M	0.81	22.23	20.60	0.070	0.0646	55	333	0.488	0.333	2.303	4.309
1	K	1.65	28.58	25.27	0.090	0.0792	139	502	1.249	0.502	3.634	6.812
	L	1.27	28.58	26.04	0.090	0.0817	109	532	0.973	0.532	2.792	5.240
	M	0.89	28.58	26.80	0.090	0.0841	77	564	0.691	0.564	1.958	3.668
1 1/4	K	1.65	34.93	31.62	0.110	0.0994	173	785	1.543	0.785	2.972	5.571
	L	1.40	34.93	32.13	0.110	0.1009	147	811	1.316	0.811	2.517	4.716
	M	1.07	34.93	32.79	0.110	0.1030	114	845	1.015	0.845	1.924	3.599
	DWV	1.02	34.93	32.89	0.110	0.1033	108	850	0.967	0.850	1.827	3.427

Table 5.2 Copper Tube Data [2017F, Ch 22, Tbl 17] ***(Continued)***

U.S. Nominal Size, in.	Type	Wall Thickness t, mm	Diameter		Surface Area		Cross Section		Mass		Working Pressure[a,b,c] ASTM B88 to 120°C MPa (gage)	
			Outside D, mm	Inside d, mm	Outside, m^2/m	Inside, m^2/m	Metal Area, mm^2	Flow Area, mm^2	Tube, kg/m	Water, kg/m	Annealed	Drawn
1 1/2	K	1.83	41.28	37.62	0.130	0.1183	226	1 111	2.025	1.111	2.786	5.226
	L	1.52	41.28	38.23	0.130	0.1201	190	1 148	1.701	1.148	2.324	4.351
	M	1.24	41.28	38.79	0.130	0.1219	157	1 181	1.399	1.182	1.896	3.558
	DWV	1.07	41.28	39.14	0.130	0.1228	135	1 203	1.204	1.203	1.627	3.048
2	K	2.11	53.98	49.76	0.170	0.1564	343	1 945	3.070	1.945	2.455	4.606
	L	1.78	53.98	50.42	0.170	0.1585	292	1 997	2.606	1.997	2.069	3.951
	M	1.47	53.98	51.03	0.170	0.1603	243	2 045	2.171	2.045	1.717	3.220
	DWV	1.07	53.98	51.84	0.170	0.1628	177	2 111	1.585	2.111	1.241	2.331
2 1/2	K	2.41	66.68	61.85	0.209	0.1942	487	3 004	4.35	3.004	2.275	4.268
	L	2.03	66.68	62.61	0.209	0.1966	413	3 079	3.69	3.079	1.917	3.592
	M	1.65	66.68	63.37	0.209	0.1990	337	3 154	3.02	3.154	1.558	2.917
3	K	2.77	79.38	73.84	0.249	0.2320	666	4 282	5.96	4.282	2.193	4.109
	L	2.29	79.38	74.80	0.249	0.2350	554	4 395	4.95	4.395	1.813	3.392
	M	1.83	79.38	75.72	0.249	0.2378	446	4 503	3.98	4.503	1.448	2.717
	DWV	1.14	79.38	77.09	0.249	0.2423	281	4 667	2.51	4.667	0.903	1.696
3 1/2	K	3.05	92.08	85.98	0.289	0.2701	852	5 806	7.62	5.806	2.082	3.903
	L	2.54	92.08	87.00	0.289	0.2733	714	5 944	6.39	5.944	1.738	3.254
	M	2.11	92.08	87.86	0.289	0.2761	596	6 063	5.33	6.063	1.441	2.703
4	K	3.40	104.78	97.97	0.329	0.3078	1084	7 538	9.69	7.538	2.041	3.827
	L	2.79	104.78	99.19	0.329	0.3115	895	7 727	8.00	7.727	1.675	3.144
	M	2.41	104.78	99.95	0.329	0.3139	776	7 846	6.94	7.846	1.448	2.717
	DWV	1.47	104.78	101.83	0.329	0.3200	478	8 144	4.27	8.144	0.883	1.655

Table 5.2 Copper Tube Data [2017F, Ch 22, Tbl 17] ***(Continued)***

U.S. Nominal Size, in.	Type	Wall Thickness t, mm	Diameter		Surface Area		Cross Section		Mass		Working Pressure[a,b,c] ASTM B88 to 120°C MPa (gage)	
			Outside D, mm	Inside d, mm	Outside, m^2/m	Inside, m^2/m	Metal Area, mm^2	Flow Area, mm^2	Tube, kg/m	Water, kg/m	Annealed	Drawn
5	K	4.06	130.18	122.05	0.409	0.3834	1610	11 699	14.39	11.70	1.965	3.682
	L	3.18	130.18	123.83	0.409	0.3889	1266	12 042	11.32	12.04	1.531	2.875
	M	2.77	130.18	124.64	0.409	0.3917	1108	12 201	9.91	12.20	1.338	2.510
	DWV	1.83	130.18	126.52	0.409	0.3975	737	12 572	6.59	12.57	0.883	1.655
6	K	4.88	155.58	145.82	0.489	0.4581	2309	16 701	20.64	16.70	1.972	3.696
	L	3.56	155.58	148.46	0.489	0.4663	1698	17 311	15.18	17.31	1.434	2.696
	M	3.10	155.58	149.38	0.489	0.4694	1484	17 525	13.27	17.53	1.255	2.351
	DWV	2.11	155.58	151.36	0.489	0.4755	1016	17 993	9.09	17.99	0.855	1.600
8	K	6.88	206.38	192.61	0.648	0.6050	4314	29 137	38.56	29.14	2.096	3.930
	L	5.08	206.38	196.22	0.648	0.6163	3212	30 238	28.71	30.24	1.544	2.903
	M	4.32	206.38	197.74	0.648	0.6212	2741	30 710	24.50	30.71	1.317	2.468
	DWV	2.77	206.38	200.84	0.648	0.6309	1771	31 680	15.83	31.62	0.841	1.579
10	K	8.59	257.18	240.00	0.808	0.7541	6705	45 241	59.93	45.15	2.096	3.937
	L	6.35	257.18	244.48	0.808	0.7681	5004	46 942	44.73	46.94	1.551	2.910
	M	5.38	257.18	246.41	0.808	0.7742	4259	47 686	38.07	47.69	1.317	2.468
12	K	10.29	307.98	287.40	0.968	0.9028	9621	64 873	85.99	64.87	2.103	3.937
	L	7.11	307.98	293.75	0.968	0.9229	6722	67 771	60.09	67.77	1.455	2.724
	M	6.45	307.98	295.07	0.968	0.9269	6112	68 382	54.63	68.38	1.317	2.468

[a]When using soldered or brazed fittings, the joint determines the limiting pressure.
[b]Working pressures were calculated using ASME Standard B31.9 allowable stresses. A 5% mill tolerance has been used on the wall thickness. Higher tube ratings can be calculated using the allowable stress for lower temperatures.
[c]If soldered or brazed fittings are used on hard drawn tubing, use the annealed ratings. Full-tube allowable pressures can be used with suitably rated flare or compression-type fittings.

Table 5.3 Properties of Pipe Materials[a] [2017F, Ch 22, Tbl 18]

Material			Tensile Strength, MPa (at 23°C)	Hydrostatic[b] Design Stress, MPa (at 23°C)		Upper Temperature Limit, °C		HDS[b] Upper Limit, MPa	Density, kg/m³	Impact Strength, N (at 23°C)	Modulus of Elasticity, GPa (at 23°C)	Coefficient of Expansion, μm/(m·K)	Thermal Conductivity, W/(m·K)	Relative Pipe Cost[c]
Designation	Type and Grade	Cell No.		Mfr.	ASME B31	Mfr.	ASME B31							
Metals														
Copper	Type L	Drawn	248		62		204	56	8900		117	17.1	33.5	3.5
Steel	A 53 B	ERW	413		88		427	63	7800	1600	190	11.4	3.8	1.3
Stainless steel	304	Drawn or Welded					177		7900		193	17.6	1.2	
Thermoplastics														
PVC 1120	T I,G1	12454-B	52	14	14	60	66	3.0	1400	43	2.90	54	0.159	1.0
PVC 1200	T I,G2	12454-C			14		66				2.83	63		
PVC 2120	T II,G1	14333-D			14		66					54		
CPVC 4120	T IV,G1	23447-B	55	14	14	99	99	2.2	1550	80	2.92	63	0.137	2.9
PE 2306	Gr. P23				4.3		60				0.62	144		
PE 3306	Gr. P34				4.3		70				0.90	126		
PE 3406	Gr. P33				4.3		82				1.03	108		
HDPE 3408	Gr. P34	355434-C	34	11	5.5	60	82	5.5	960	640	0.76	216	0.389	1.1
PP			34	4.9		100	99		910	70	0.83	108	0.187	2.9
ABS	Acrylonitrile copolymer	6-3-3	38			80			1060	450	1.65	101	0.245	3.4
ABS 1210	T I,G2	5-2-2			7		82	4.4			1.72	99		
ABS 1316	T I,G3	3-5-5			11		82	6.9			2.34	72		
ABS 2112	T II,G1	4-4-5			8.6		82	5.5				72		
PVDF			48	8.8		138	135	2.1	1780	200	0.86	142	0.115	28.0

Table 5.3 Properties of Pipe Materials[a] [2017F, Ch 22, Tbl 18] *(Continued)*

Material			Tensile Strength, MPa (at 23°C)	Hydrostatic[b] Design Stress, MPa (at 23°C)		Upper Temperature Limit, °C		HDS[b] Upper Limit, MPa	Density, kg/m^3	Impact Strength, N (at 23°C)	Modulus of Elasticity, GPa (at 23°C)	Coefficient of Expansion, μm/(m·K)	Thermal Conductivity, W/(m·K)	Relative Pipe Cost[c]
Designation	Type and Grade	Cell No.		Mfr.	ASME B31	Mfr.	ASME B31							
Thermosetting														
Epoxy-glass	RTRP-11AF		303	55		99		48			6.90	16 to 23	0.418	
PEX	A,B,C[d]		22	4.3		93	82	0.54	940	200	0.52	162	0.462	0.75
Polyester-glass	RTRP-12EF		303	62		93		34			6.90	16 to 20	0.187	
For Comparison														
Steel	A 53 B	ERW	413		88		427	63	7800	1600	190	11.4	49.6	1.3
Copper	Type L	Drawn	248		62		204	56	8900		117	17.1		3.5

[a] Properties listed are for the specific materials listed; each plastic has other formulations. Consult the manufacturer of the system chosen. These values are for comparative purposes.
[b] Hydrostatic design stress (HDS) is equivalent to allowable design stress.
[c] Based on cost of pipe only, without factoring in fittings, joints, hangers, and labor.
[d] A, B, and C are the three manufacturing processes of PEX pipe. The classifications are not related to a ranking system.

Table 5.4 Common Applications of Pipe, Fittings, and Valves for Heating and Air Conditioning [2017F, Ch 22, Tbl 1]

Application	Size, mm	Material	Type	Joint Type	Fitting Material	Class (When Applicable)	System[g] Temperature, °C	Maximum Pressure at Temperature,[a,b] kPa
Chilled water	≤51	Steel Type F (CW)	Schedule 40	Thread	Cast iron	125	121	862
	62.5 to 305	Steel A or B, Type E (ERW)	Schedule 40	Weld	Wrought steel	Standard	121	2758
				Flange	Wrought steel	150	121	1724
					Cast iron	125	121	1207
					Cast iron	250	121	2758
		Copper, hard or soft	Type K or L	Solder	Wrought or cast Cu		38	2586 Type K soft
				Flared (soft)				4378 Type K hard
				Rolled groove (51 to 203)				1724 Type L soft
				Press-connect (13 to 102)				2999 Type L hard
				Push connect (13 to 51)				
				Mechanical formed				
				Braze	Wrought or cast Cu		38	1724 Type L soft
				Weld				2586 Type K soft
		Copper, hard	Type M	Solder	Wrought or cast Cu		38	2724 Type M hard
				Rolled groove (51 to 203)				
				Press-connect (13 to 102)				
				Push connect (13 to 51)				
				Mechanical formed				
				Braze	Wrought or cast Cu		38	1586 Type M soft
				Weld				
	10 to 25	PEX (barrier)	SDR-9	Crimp	Bronze		23	1000
				Clamp	Brass			
				Expansion	Copper			
				Compression	Engineered plastic			
				Push fit				
				Proprietary				

Table 5.4 Common Applications of Pipe, Fittings, and Valves for Heating and Air Conditioning [2017F, Ch 22, Tbl 1] ***(Continued)***

Application	Size, mm	Material	Type	Joint Type	Fitting Material	Class (When Applicable)	System[g] Temperature, °C	Maximum Pressure at Temperature,[a,b] kPa
Chilled water (cont'd)	13 to 152	PE	Schedule 40,[f] 80, SDR	Thermal fusion, compression	PE		49 (60 limit for some applications)	Varies with pipe wall thickness, grade, schedule, size. Check manufacturer's documentation for design ratings 207 to 758 at 54°C
Heating and recirculating	51 and smaller	Steel Type F (CW)	Schedule 40	Thread	Cast iron	125	121	862
	6 to 305	Steel B Type E (ERW)	Schedule 40	Weld	Wrought steel	Standard	121	2758
				Flange	Wrought steel	150	121	1724
					Cast iron	125	121	862
					Cast iron	250	121	2758
		Copper, hard or soft	Type K or L	Solder Braze Flared (soft) Rolled groove (51 to 203) Press-connect (13 to 102) Push connect (13 to 51) Mechanical formed	Wrought or cast Cu		93	2069 Type K soft 4378 Type K hard 1413 Type L soft 2999 Type L hard
				Braze Weld	Wrought or cast Cu		93	2069 Type K soft 1413 Type L soft
	6 to 305	Copper, hard	Type M	Solder Rolled groove (51 to 203) Press-connect (13 to 102) Push connect (13 to 51) Mechanical formed	Wrought or cast Cu		93	2724 Type M hard
				Braze Weld	Wrought or cast Cu		93	1379 Type M soft

Table 5.4 Common Applications of Pipe, Fittings, and Valves for Heating and Air Conditioning [2017F, Ch 22, Tbl 1] ***(Continued)***

Application	Size, mm	Material	Type	Joint Type	Fitting Material	Class (When Applicable)	System[g] Temperature, °C	Maximum Pressure at Temperature,[a,b] kPa
Heating and recirculating (cont'd)	10 to 25	PEX (barrier)	SDR-9	Crimp	Bronze		93	545
				Clamp	Brass			
				Expansion	Copper			
				Compression	Engineered plastic			
				Push fit				
				Proprietary				
Steam and condensate	51 and smaller	Steel Type F (CW) or S	Schedule 40[d]	Thread	Cast iron	125		621
				Thread	Malleable iron	150		621
				Socket	Forged steel	3000		621
		Steel B Type E (ERW) or S	Schedule 40[d]	Thread	Cast iron	125		690
				Thread	Malleable iron	150		862
				Socket	Forged steel	3000		2758
		Steel B Type E (ERW) or S	Schedule 80	Thread	Cast iron	250		1379
				Socket				
				Thread	Malleable iron	300		1724
				Socket	Forged steel	3000		2758
	51 to 305	Steel B Type E (ERW) or S	Schedule 40	Weld	Wrought steel	Standard		1724
				Flange	Wrought steel	150		1379
					Cast iron	125		690
		Steel B Type E (ERW) or S	Schedule 80	Weld	Wrought steel	XS		4826
				Flange	Wrought steel	300		3448
					Cast iron	250		1379

Table 5.4 Common Applications of Pipe, Fittings, and Valves for Heating and Air Conditioning [2017F, Ch 22, Tbl 1] ***(Continued)***

Application	Size, mm	Material	Type	Joint Type	Fitting Material	Class (When Applicable)	System[g] Temperature, °C	Maximum Pressure at Temperature,[a,b] kPa
Ground-source heat pump	6 to 51	Copper, hard or soft	Type L or ACR	Flared or brazed	Wrought or cast Cu		93	1413 Type L soft, 2999 Type L hard, 4655 ACR soft, 3448 ACR hard
	10 to 25	PEX (barrier)	SDR-9	Crimp Clamp Expansion Compression Push fit Proprietary	Bronze Brass Copper Engineered plastic		82	690
Refrigerant	10 to 105	Steel B Type E (ERW)	Schedule 40	Weld			Wrought steel	
		Copper, hard	Type L or ACR	Braze	Wrought or Forged Cu		93	2999 Type L hard, 4655 ACR soft
Natural gas and LP	6 to 305	Copper, hard or soft	Type K or L	Solder Rolled groove (51 to 203) Press-connect (13 to 102) Push connect (13 to 51) Mechanically formed	Wrought or cast Cu		38	2551 Type K soft 4378 Type K hard 1724 Type L soft 2999 Type L hard
				Braze Weld	Wrought or cast Cu		38	2551 Type K soft 1724 Type L soft
	10 to 105	Copper, hard	ACR	Solder	Wrought or cast Cu		38	3448 Type ACR hard
				Braze	Wrought or cast Cu		38	2000 Type ACR Soft
	10 to 25	PEX	SDR-9	Crimp Clamp Expansion Compression Push fit Proprietary	Bronze Brass Copper Engineered plastic		23	1000

Table 5.4 Common Applications of Pipe, Fittings, and Valves for Heating and Air Conditioning [2017F, Ch 22, Tbl 1] ***(Continued)***

Application	Size, mm	Material	Type	Joint Type	Fitting Material	Class (When Applicable)	System[g] Temperature, °C	Maximum Pressure at Temperature,[a,b] kPa
Natural gas and LP (cont'd)	13 to 152	PE	Schedule 40, 80, SDR	Thermal fusion, compression	PE		49 (60limit for some applications)	Depends on pipe, grade, schedule, size. Generally 207 to 758 at 54°C
	13 to 152	HDPE	SDR	Thermal fusion, compression	HDPE		49	Depends on pipe, grade, schedule, size. Generally 441 for SDR 11 at 49°C
Fuel oil, aboveground	51 to 305	Black Steel, B Type E (ERW) or S (seamless)	Schedule 40	Thread or weld	Black malleable iron Wrought steel weld Forged steel flanges	150 150		
	6 to 305	Copper, hard or soft	Type K or L	Solder Flared (soft) Rolled groove (51 to 203) Press-connect (13 to 102) Push connect (13 to 51) Mechanical formed	Wrought or cast Cu		38	2069 Type K soft 4378 Type K hard 1724 Type L soft 2999 Type L hard
				Braze or weld	Wrought or cast Cu		38	2069 Type K soft, 1724 Type L soft
		Copper, hard	Type M	Solder Braze Rolled groove (51 to 203) Press-connect (13 to 102) Push connect (13 to 51) Mechanical formed	Wrought or cast Cu		38	2724 Type M hard

Table 5.4 Common Applications of Pipe, Fittings, and Valves for Heating and Air Conditioning [2017F, Ch 22, Tbl 1] ***(Continued)***

Application	Size, mm	Material	Type	Joint Type	Fitting Material	Class (When Applicable)	System[g] Temperature, °C	Maximum Pressure at Temperature,[a,b] kPa
Fuel oil, aboveground (cont'd)	6 to 305	ABS	Schedule 40,[f] 80, SDR	Solvent weld, thread, flange	ABS		71 limit	Depends on pipe class: approximately 345 at 71°C
	13 to 152	HDPE	SDR-9	Thermal fusion, compression	HDPE		49	Depends on pipe, grade, schedule, size. Generally 441 for SDR 11 at 49°C
Compressed air	≤62.5 and smaller	Black steel	Schedule 40	Thread	Black malleable iron	150	177	
	>62.5	Black steel	Schedule 40	Flange or weld	Black malleable iron	150	177	
	10 to 105	Copper, hard	ACR	Solder Flared (soft) Mechanical formed Braze	Wrought or cast Cu		93 93	4655 ACR soft 3448 ACR hard 4655 ACR hard
	13 to 102	ABS HDPE	Schedule 40 Schedule 40, 80, SDR	Solvent weld	ABS HDPE		23	1276
	10 to 25	PEX	SDR-9					
Potable water, inside building	6 to 305	Steel, galvanized	Schedule 40	Thread	Galv. cast iron Galv. cast iron	150 150	38 38	862 1034
		Copper, hard or soft	Type K or L	Solder[c] Flared (soft) Rolled groove (51 to 203) Press-connect (13 to 102) Push connect (13 to 51) Mechanical formed Braze Weld	Wrought or cast Cu Wrought or cast Cu		38 38	2551 Type K soft 4378 Type K hard 1724 Type L soft 2999 Type L hard 2551 Type K soft 1724 Type L soft

Table 5.4 Common Applications of Pipe, Fittings, and Valves for Heating and Air Conditioning [2017F, Ch 22, Tbl 1] ***(Continued)***

Application	Size, mm	Material	Type	Joint Type	Fitting Material	Class (When Applicable)	System[g] Temperature, °C	Maximum Pressure at Temperature,[a,b] kPa
Potable water, inside building (cont'd)	6 to 305	Copper, hard	Type M	Solder[c] Rolled groove (51 to 203) Press-connect (13 to 102) Push connect (13 to 51) Mechanical formed	Wrought or cast Cu		38	2724 Type M hard
				Braze Weld	Wrought or cast Cu		38	1586 Type M soft
	13 to 203	CPVC	Schedule 40,[f] 80		CPVC		99 Limit, 93 operating	
	10 to 25	PEX	SDR-9	Crimp Clamp Expansion Compression Push fit Proprietary	Bronze Brass Copper Engineered plastic		38	1000
	13 to 152	PE	Schedule 40,[f] 80, SDR	Thermal fusion, compression	PE		49 (60 limit for some applications)	Depends on pipe, grade, schedule, size generally 207 to 758 at 54°C
	13 to 152	PP	Schedule 40,[f] 80, SDR	Thermal fusion, flange, Thread[e]	PP		82	345

Table 5.4 Common Applications of Pipe, Fittings, and Valves for Heating and Air Conditioning [2017F, Ch 22, Tbl 1] ***(Continued)***

Application	Size, mm	Material	Type	Joint Type	Fitting Material	Class (When Applicable)	System[g] Temperature, °C	Maximum Pressure at Temperature,[a,b] kPa
Water services, underground	Through 152	Ductile iron	Class 50	Mechanical joint	Cast iron		24	1724
	6 to 305	Copper, hard or soft	Type K or L	Solder[c]	Wrought or cast Cu		38	2551 Type K soft 4378 Type K hard 1724 Type L soft 2999 Type L hard
				Flared (soft)				
				Rolled groove (51 to 203)				
				Press-connect (13 to 102)				
				Push connect (13 to 51)				
				Mechanical formed				
				Braze	Wrought or cast Cu		38	2551 Type K soft 1724 Type L soft
				Weld				
				Flange	Bronze		38	
	6 to 305	Copper, hard	Type M	Solder[c]	Wrought or cast Cu		38	2724 Type K hard
				Rolled groove (51 to 203)				
				Press-connect (13 to 102)				
				Push connect (13 to 51)				
				Mechanical formed				
				Braze	Wrought or cast Cu		38	1586 Type M soft
				Weld				
	10 to 25	PEX	SDR-9	Crimp	Bronze		23	1000
				Clamp	Brass			
				Expansion	Copper			
				Compression	Engineered plastic			
				Push fit				
				Proprietary				
	6 to 508	PVC	Schedule 40, 80, 120, SDR	Solvent weld, thread,[f] thermal weld	PVC		66 limit, 60 operating	545 to 724, depending on schedule and size

Table 5.4 Common Applications of Pipe, Fittings, and Valves for Heating and Air Conditioning [2017F, Ch 22, Tbl 1] ***(Continued)***

Application	Size, mm	Material	Type	Joint Type	Fitting Material	Class (When Applicable)	System[g] Temperature, °C	Maximum Pressure at Temperature,[a,b] kPa
Drainage, waste, and vent (DWV)	32 to 203	Copper, hard	DWV	Solder	Wrought or cast Cu		38	1724 DWV hard
	32 to 305	ABS	Schedule DWV, 40,[f] 80, SDR	Solvent weld, thread, flange	ABS		71 limit	Depends on pipe class: approximately 345 at 71°C
	32 to 508	PV	Schedule 40,[f] 80, 120, SDR	Solvent weld, thread, thermal weld	PVC		66 limit, 60 operating	545 to 724, depending on schedule and size

[a]Maximum allowable working pressures have been derated in this table. Higher system pressures can be used for lower temperatures and smaller pipe sizes. Pipe, fittings, joints, and valves must all be considered.
[b]Temperature and pressure relationships can vary based on pipe material composition, size, class, and schedule.
[c]Lead- and antimony-based solders are prohibited for potable water systems. Brazing should be used.
[d]Piping codes typically require thicker-walled pipe for threaded joints to maintain corrosion allowance and pressure ratings.
[e]All plumbing codes require both hot and cold water piping to have a 689 kPa at 82°C rating.
[f]Threads are not recommended on Schedule 40 plastic pipe.
[g]Designer should confirm that all materials are suitably rated for intended operation.

Table 5.5 Thermal Expansion of Metal Pipe [2017F, Ch 22, Tbl 13]

	Saturated Steam Pressure, kPa (gage)	Temperature, °C	Linear Thermal Expansion, mm/m		
			Carbon Steel	Type 304 Stainless Steel	Copper
		–34	–0.16	–0.25	–0.27
		–29	–0.10	–0.17	–0.18
		–23	–0.05	–0.08	–0.09
		–18	0	0	0
		–12	0.07	0.09	0.10
		–7	0.13	0.18	0.20
Vacuum	–100.7	0	0.20	0.30	0.31
Vacuum	–100.7	4	0.25	0.38	0.38
Vacuum	–100.0	10	0.32	0.47	0.47
Vacuum	–99.3	16	0.38	0.56	0.57
Vacuum	–98.6	21	0.44	0.65	0.66
Vacuum	–97.9	27	0.51	0.75	0.75
Vacuum	–96.5	32	0.57	0.84	0.85
Vacuum	–94.5	38	0.63	0.93	0.94
Vacuum	–89.6	49	0.76	1.13	1.14
Vacuum	–81.4	60	0.88	1.31	1.33
Vacuum	–69.0	71	1.02	1.49	1.50
Vacuum	–49.6	82	1.14	1.68	1.71
Vacuum	–22.1	93	1.27	1.87	1.92
	0	100	1.35	1.98	2.03
	17.2	104	1.41	2.07	2.10
	71.0	116	1.54	2.26	2.30
	142.7	127	1.68	2.45	2.49
	238.6	138	1.82	2.64	2.68
	360.6	149	1.96	2.83	2.88
	517.1	160	2.11	3.03	3.08
	712.3	171	2.25	3.23	3.28
	953.6	182	2.40	3.43	3.48
	1 249	193	2.54	3.63	3.68
	1 604	204	2.69	3.83	4.06
	9 039	304	4.11	5.65	5.77
		404	5.67	7.56	7.72
		504	7.31	9.54	9.76

Table 5.6 Suggested Hanger Spacing and Rod Size for Straight Horizontal Runs
[2017F, Ch 22, Tbl 11]

Nominal O.D., mm	Hanger Spacing, m			Rod Size, mm
	Standard Steel Pipe*		Copper Tube	
	Water	Steam	Water	
15	2.1	2.4	1.5	6.4
20	2.1	2.7	1.5	6.4
25	2.1	2.7	1.8	6.4
40	2.7	3.7	2.4	10
50	3.0	4.0	2.4	10
65	3.4	4.3	2.7	10
80	3.7	4.6	3.0	10
100	4.3	5.2	3.7	13
150	5.2	6.4	4.3	13
200	5.8	7.3	4.9	16
250	6.1	7.9	5.5	19
300	7.0	9.1	5.8	22
350	7.6	9.8		25
400	8.2	10.7		25
450	8.5	11.3		32
500	9.1	11.9		32

Source: Adapted from MSS Standard SP-69

*Spacing does not apply where span calculations are made or where concentrated loads are placed between supports such as flanges, valves, specialties, etc.

Table 5.7 Capacities of ASTM A36 Steel Threaded Rods
[2017F, Ch 22, Tbl 10]

Rod Diameter, mm	Root Area of Coarse Thread, mm^2	Maximum Load,[a] N
6.4	17.4	1 070
10	43.9	2 720
13	81.3	5 030
16	130.3	8 060
19	194.8	12 100
22	270.3	16 800
25	356.1	22 100
32	573.5	35 600

[a] Based on an allowable stress of 83 MPa reduced by 25% using the root area in accordance with ASME Standard B31.1 and MSS Standard SP-58.

6. SERVICE WATER HEATING

Water heating energy use is second only to space conditioning in most residential buildings, and is also significant in many commercial and industrial settings. In some climates and applications, water heating is the largest energy use in a building. Moreover, quick availability of adequate amounts of hot water is an important factor in user satisfaction. Both water and energy waste can be significant in poorly designed service water-heating systems: from over- or undersizing pipes and equipment, from poor building layout, and from poor system design and operating strategies. Good service water-heating system design and operating practices can often reduce first costs as well as operating costs.

System Elements

A service water-heating system has (1) one or more heat energy sources, (2) heat transfer equipment, (3) a distribution system, and (4) terminal hot-water usage devices.

Heat energy sources may be (1) fuel combustion; (2) electrical conversion; (3) solar energy; (4) geothermal, air, or other environmental energy; and/or (5) recovered waste heat from sources such as flue gases, ventilation and air-conditioning systems, refrigeration cycles, and process waste discharge.

Heat transfer equipment is direct, indirect, or a combination of the two. For direct equipment, heat is derived from combustion of fuel or direct conversion of electrical energy into heat and is applied within the water-heating equipment. For indirect heat transfer equipment, heat energy is developed from remote heat sources (e.g., boilers; solar energy collection; air, geothermal, or other environmental source; cogeneration; refrigeration; waste heat) and is then transferred to the water in a separate piece of equipment. Storage tanks may be part of or associated with either type of heat transfer equipment.

Distribution systems transport hot water produced by water-heating equipment to terminal hot-water usage devices. Water consumed must be replenished from the building water service main. For locations where constant supply temperatures are desired, circulation piping or a means of heat maintenance must be provided.

Terminal hot-water usage devices are plumbing fixtures and equipment requiring hot water that may have periods of irregular flow, constant flow, and no flow. These patterns and their related water usage vary with different buildings, process applications, and personal preference.

Legionella pneumophila (Legionnaires' Disease)

Legionnaires' disease (a form of severe pneumonia) is caused by inhaling the bacteria *Legionella pneumophila*. It has been discovered in the service water systems of various buildings throughout the world.

Service water temperature in the 60°C range is recommended to limit the potential for *L. pneumophila* growth. This high temperature increases the potential for scalding, so care must be taken such as installing an anti-scald or mixing valve.

More information on this subject can be found in ASHRAE Standard 188 and ASHRAE Guideline 12.

Load Diversity

The greatest difficulty in designing water-heating systems comes from uncertainty about design hot-water loads, especially for buildings not yet built. Although it is fairly simple to test maximum flow rates of various hot-water fixtures and appliances, actual flow rates and durations are user-dependent. Moreover, the timing of different hot-water use events varies from day to day, with some overlap, but almost never will all fixtures be used simultaneously. As the number of hot-water-using fixtures and appliances grows, the percent of those fixtures used simultaneously decreases.

Some of the hot-water load information here is based on limited-scale field testing combined with statistical analysis to estimate load demand or **diversity** factors (percent of total possible load that is ever actually used at one time) versus number of end use points, number of people, etc. Much of the work to provide these diversity factors dates from the 1930s to the 1960s; it remains, however, the best information currently available (with a few exceptions, as noted). Of greatest concern is the fact that most of the data from those early studies were for fixtures that used water at much higher flow rates than modern energy-efficient fixtures (e.g., low-flow shower heads and sink aerators, energy-efficient washing machines and dishwashers). Using the older load diversity information usually results in a water-heating system that adequately serves the loads, but often results in substantial oversizing. Oversizing can be a deterrent to using modern high-efficiency water-heating equipment, which may have higher first cost per unit of capacity than less efficient equipment.

Table 6.1 Typical Residential Use of Hot Water [2015A, Ch 50, Tbl 3]

Use	High Flow, Litres/Task	Low Flow (Water Savers Used), Litres/Task	Ultralow Flow, Litres/Task
Food preparation	19	11	11
Hand dish washing	15	15	11
Automatic dishwasher	57	57	11 to 38
Clothes washer	121	80	19 to 57
Shower or bath	76	57	38 to 57
Face and hand washing	15	8	4 to 8

Table 6.2 HUD-FHA Minimum Water Heater Capacities for One- and Two-Family Living Units [2015A, Ch 50, Tbl 4]

Number of Baths	1 to 1.5			2 to 2.5				3 to 3.5			
Number of Bedrooms	**1**	**2**	**3**	**2**	**3**	**4**	**5**	**3**	**4**	**5**	**6**
Gas[a]											
Storage, L	76	114	114	114	150	150	190	150	190	190	190
kW input	7.9	10.5	10.5	10.5	10.5	11.1	13.8	11.1	11.1	13.8	14.6
1 h draw, L	163	227	227	227	265	273	341	273	311	341	350
Recovery, mL/s	24	32	32	32	32	36	42	34	34	42	44
Electric[a]											
Storage, L	76	114	150	150	190	190	250	190	250	250	300
kW input	2.5	3.5	4.5	4.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
1 h draw, L	114	167	220	220	273	273	334	273	334	334	387
Recovery, mL/s	10	15	19	19	23	23	23	23	23	23	23
Oil[a]											
Storage, L	114	114	114	114	114	114	114	114	114	114	114
kW input	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1 h draw, L	337	337	337	337	337	337	337	337	337	337	337
Recovery, mL/s	62	62	62	62	62	62	62	62	62	62	62
Tank-Type Indirect[b,c]											
I-W-H-rated draw, L in 3 h, 55 K rise		150	150		250	250[e]	250	250	250	250	250
Manufacturer-rated draw, L in 3 h, 55 K rise		186	186		284	284[e]	284	284	284	284	284
Tank capacity, L		250	250		250	250[e]	310	250	310	310	310
Tankless-Type Indirect[c,d]											
I-W-H-rated draw, mL/s, 55 K rise		170	170		200	200[e]	240	200	240	240	240
Manufacturer-rated draw, L in 5 min, 55 K rise		57	57		95	95[e]	133	95	133	133	133

Note: Applies to tank-type water heaters only.

[a]Storage capacity, input, and recovery requirements indicated are typical and may vary with manufacturer. Any combination of requirements to produce stated 1 h draw is satisfactory.

[b]Boiler-connected water heater capacities (82°C boiler water, internal or external connection).

[c]Heater capacities and inputs are minimum allowable. Variations in tank size are permitted when recovery is based on 4.2 mL/(s·kW) at 55 K rise for electrical, AGA recovery ratings for gas, and IBR ratings for steam and hot-water heaters.

[d]Boiler-connected heater capacities (93°C boiler water, internal or external connection).

[e]Also for 1 to 1.5 baths and 4 bedrooms for indirect water heaters.

Table 6.3 Overall (OVL) and Peak Average Hot-Water Use [2015A, Ch 50, Tbl 5]

Group	Average Hot-Water Use, L							
	Hourly		Daily		Weekly		Monthly	
	OVL	Peak	OVL	Peak	OVL	Peak	OVL	Peak
All families	9.8	17.3	236	254	1652	1873	7178	7700
“Typical” families	9.9	21.9	239	252	1673	1981	7270	7866

Table 6.4 Hot-Water Demands and Use for Various Types of Buildings*
[2015A, Ch 50, Tbl 6]

Type of Building	Maximum Hourly	Maximum Daily	Average Daily
Men's dormitories	14.4 L/student	83.3 L/student	49.7 L/student
Women's dormitories	19 L/student	100 L/student	46.6 L/student
Motels: Number of units[a]			
20 or less	23 L/unit	132.6 L/unit	75.8 L/unit
60	20 L/unit	94.8 L/unit	53.1 L/unit
100 or more	15 L/unit	56.8 L/unit	37.9 L/unit
Nursing homes	17 L/bed	114 L/bed	69.7 L/bed
Office buildings	1.5 L/person	7.6 L/person	3.8 L/person
Food service establishments:			
Type A: Full-meal restaurants and cafeterias	5.7 L/max meals/h	41.7 L/max meals/day	9.1 L/average meals/day[b]
Type B: Drive-ins, grills, luncheonettes, sandwich and snack shops	2.6 L/max meals/h	22.7 L/max meals/day	2.6 L/average meals/day[b]
Apartment houses: Number of apartments			
20 or less	45.5 L/apartment	303.2 L/apartment	159.2 L/apartment
50	37.9 L/apartment	276.7 L/apartment	151.6 L/apartment
75	32.2 L/apartment	250 L/apartment	144 L/apartment
100	26.5 L/apartment	227.4 L/apartment	140.2 L/apartment
200 or more	19 L/apartment	195 L/apartment	132.7 L/apartment
Elementary schools	2.3 L/student	5.7 L/student	2.3 L/student[b]
Junior and senior high schools	3.8 L/student	13.6 L/student	6.8 L/student[b]

*Data predate modern low-flow fixtures and appliances.
[a]Interpolate for intermediate values.[b]Per day of operation.

Table 6.5 Hot Water Demand per Fixture for Various Types of Buildings [2015A, Ch 50, Tbl 10]
(Litres of water per hour per fixture, calculated at a final temperature of 60°C)

	Apartment House	Club	Gymnasium	Hospital	Hotel	Industrial Plant	Office Building	Private Residence	School	YMCA
1. Basin, private lavatory	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
2. Basin, public lavatory	15	23	30	23	30	45.5	23	—	57	30
3. Bathtub[c]	76	76	114	76	76	—	—	76	—	114
4. Dishwasher[a]	57	190-570	—	190-570	190-760	76-380	—	57	76-380	76-380
5. Foot basin	11	11	46	11	11	46	—	11	11	46
6. Kitchen sink	38	76	—	76	114	76	76	38	76	76
7. Laundry, stationary tub	76	106	—	106	106	—	—	76	—	106
8. Pantry sink	19	38	—	38	38	—	38	19	38	38
9. Shower	114	568	850	284	284	850	114	114	850	850
10. Service sink	76	76	—	76	114	76	76	57	76	76
11. Hydrotherapeutic shower				1520						
12. Hubbard bath				2270						
13. Leg bath				380						
14. Arm bath				130						
15. Sitz bath				114						
16. Continuous-flow bath				625						
17. Circular wash sink				76	76	114	76		114	
18. Semicircular wash sink				38	38	57	38		57	
19. DEMAND FACTOR	0.30	0.30	0.40	0.25	0.25	0.40	0.30	0.30	0.40	0.40
20. STORAGE CAPACITY FACTOR[b]	1.25	0.90	1.00	0.60	0.80	1.00	2.00	0.70	1.00	1.00

Note: Data sources predate low-flow fixtures and appliances.
[a]Dishwasher requirements should be taken from this table or from manufacturers' data for model to be used, if known.
[b]Ratio of storage tank capacity to probable maximum demand/h. Storage capacity may be reduced where unlimited supply of steam is available from central street steam system or large boiler plant.
[c]Whirlpool baths require specific consideration based on capacity. They are not included in the bathtub category.

Table 6.6 Tankless Water Heater Output Heat Rates, kW* [2015A, Ch 50, Tbl 15]

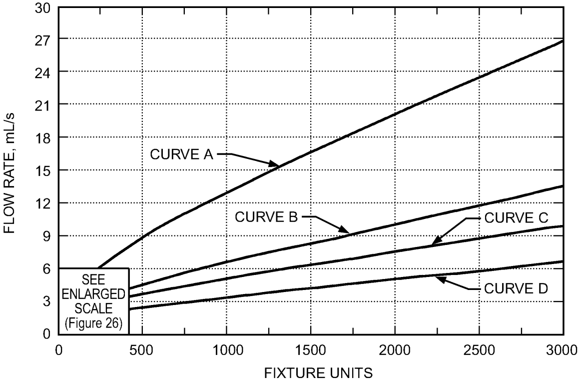
Flow Rate, mL/s	Temperature Rise						
	6 K	**14 K**	**28 K**	**31 K**	**42 K**	**43 K**	**56 K**
6.3	0.15	0.37	0.74	0.81	1.11	1.14	1.48
31.5	0.74	1.85	3.69	4.06	5.54	5.69	7.39
63.1	1.48	3.69	7.39	8.12	11.1	11.4	14.8
94.6	2.22	5.54	11.1	12.2	16.6	17.1	22.2
126	2.95	7.39	14.8	16.2	22.2	22.8	29.5
158	3.69	9.23	18.5	20.3	27.7	28.4	36.9
189	4.43	11.1	22.2	24.4	33.2	34.1	44.3
221	5.17	12.9	25.8	28.4	38.8	39.8	51.7
252	5.91	14.8	29.5	32.5	44.3	45.5	59.1
284	6.65	16.6	33.2	36.6	49.9	51.2	66.5
315	7.39	18.5	36.9	40.6	55.4	56.9	73.9
379	8.86	22.2	44.3	48.7	66.5	68.2	88.6
442	10.3	25.8	51.7	56.9	77.5	79.6	103.4
505	11.8	29.5	59.1	65.0	88.6	91.0	118.2
568	13.3	33.2	66.5	73.1	99.7	102.4	132.9
631	14.8	36.9	73.9	81.2	110.8	113.7	147.7

*Divide table values by input efficiency to determine required heat input rate.

Table 6.7 Hot-Water Demand in Fixture Units (60°C Water) [2015A, Ch 50, Tbl 16]

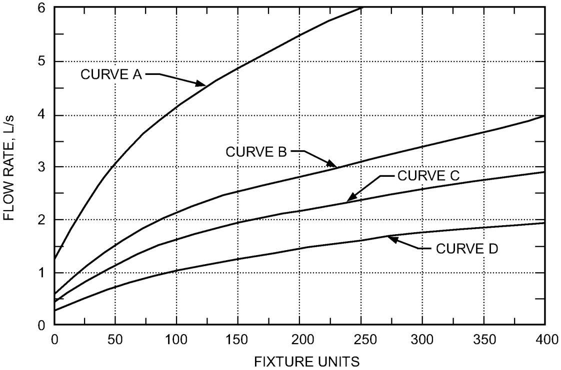
	Apartments	Club	Gymnasium	Hospital	Hotels and Dormitories	Industrial Plant	Office Building	School	YMCA
Basin, private lavatory	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Basin, public lavatory	—	1	1	1	1	1	1	1	1
Bathtub	1.5	1.5	—	1.5	1.5	—	—	—	—
Dishwasher*	1.5	Five fixture units per 250 seating capacity							
Therapeutic bath	—	—	—	5	—	—	—	—	—
Kitchen sink	0.75	1.5	—	3	1.5	3	—	0.75	3
Pantry sink	—	2.5	—	2.5	2.5	—	—	2.5	2.5
Service sink	1.5	2.5	—	2.5	2.5	2.5	2.5	2.5	2.5
Shower	1.5	1.5	1.5	1.5	1.5	3.5	—	1.5	1.5
Circular wash fountain	—	2.5	2.5	2.5	—	4	—	2.5	2.5
Semicircular wash fountain	—	1.5	1.5	1.5	—	3	—	1.5	1.5

Note: Data predate modern low-flow fixtures and appliances.



CURVE A: RESTAURANTS
CURVE B: HOSPITALS, NURSING HOMES, NURSES' RESIDENCES, DORMITORIES, HOTELS, AND MOTELS
CURVE C: APARTMENTS AND HOUSES
CURVE D: OFFICE BUILDINGS, ELEMENTARY AND HIGH SCHOOLS

Figure 6.1 Modified Hunter Curve for Calculating Hot-Water Flow Rate [2015A, Ch 50, Fig 27]
(Data Predate Modern Low-Flow Fixtures and Appliances)



CURVE A: RESTAURANTS
CURVE B: HOSPITALS, NURSING HOMES, NURSES' RESIDENCES, DORMITORIES, HOTELS, AND MOTELS
CURVE C: APARTMENTS AND HOUSES
CURVE D: OFFICE BUILDINGS, ELEMENTARY AND HIGH SCHOOLS

Figure 6.2 Enlarged Section of Modified Hunter Curve [2015A, Ch 50, Fig 28]
(Data Predate Modern Low-Flow Fixtures and Appliances)

Temperature Requirement

Typical temperature requirements for some services are shown in Table 6.8. A 60°C water temperature minimizes flue gas condensation in the equipment.

Other Safety Concerns

Regulatory agencies differ as to the selection of protective devices and methods of installation. It is therefore essential to check and comply with the manufacturer's instructions and the applicable local codes. In the absence of such instructions and codes, the following recommendations may be used as a guide:

- Water expands when it is heated. Although the water-heating system is initially under service pressure, the pressure rises rapidly if backflow is prevented by devices such as a check valve, pressure-reducing valve, or backflow preventer in the cold-water line or by temporarily shutting off the cold-water valve. When backflow is prevented, the pressure rise during heating may cause the safety relief valve to weep to relieve the pressure. However, if the safety relief valve is inadequate, inoperative, or missing, pressure rise may rupture the tank or cause other damage. Systems having this potential problem must be protected by a properly sized expansion tank located on the cold-water line downstream of and as close as practical to the device preventing backflow.
- Temperature-limiting devices (energy cutoff/high limit) prevent water temperatures from exceeding 99°C by stopping the flow of fuel or energy. These devices should be listed and labeled by a recognized certifying agency.
- Safety relief valves open when pressure exceeds the valve setting. These valves are typically applied to water-heating and hot-water supply boilers. The set pressure should not exceed the maximum allowable working pressure of the boiler. The heat input pressure steam rating (in kW) should equal or exceed the maximum out-put rating for the boiler. The valves should comply with current applicable standards or the ASME *Boiler and Pressure Vessel Code*.
- Temperature and pressure safety relief valves also open if the water temperature reaches 99°C. These valves are typically applied to water heaters and hot-water storage tanks. The heat input temperature/steam rating (in kW) should equal or exceed the heat input rating of the water heater. Combination temperature- and pressure-relief valves should be installed with the temperature-sensitive element located in the top 150 mm of the tank (i.e., where the water is hottest).
- To reduce scald hazards, discharge temperature at fixtures accessible to the occupant should not exceed 50°C. Thermostatically controlled mixing valves can be used to blend hot and cold water to maintain safe service hot-water temperatures.
- A relief valve should be installed in any part of the system containing a heat input device that can be isolated by valves. The heat input device may be solar water-heating panels, desuperheater water heaters, heat recovery devices, or similar equipment.

Table 6.8 Representative Hot-Water Temperatures [2015A, Ch 50, Tbl 19]

Use	Temperature, °C
Lavatory	
Hand washing	40
Shaving	45
Showers and tubs	43
Therapeutic baths	35
Commercial or institutional laundry, based on fabric	up to 82
Residential dish washing and laundry	60
Surgical scrubbing	43
Commercial spray-type dish washing[a]	
Single- or multiple-tank hood or rack type	
Wash	65 minimum
Final rinse	82 to 90
Single-tank conveyor type	
Wash	71 minimum
Final rinse	82 to 90
Single-tank rack or door type	
Single-temperature wash and rinse	74 minimum
Chemical sanitizing types[b]	60
Multiple-tank conveyor type	
Wash	65 minimum
Pumped rinse	71 minimum
Final rinse	82 to 90
Chemical sanitizing glass washer	
Wash	60
Rinse	24 minimum

[a]As required by NSF.

[b]See manufacturer for actual temperature required.

7. REFRIGERATION CYCLES

Refrigeration cycles transfer thermal energy from a region of low temperature T_R to one of higher temperature. Usually the higher-temperature heat sink is the ambient air or cooling water, at temperature T_0, the temperature of the surroundings.

The first and second laws of thermodynamics can be applied to individual components to determine mass and energy balances and the irreversibility of the components. This procedure is illustrated in later sections in this chapter.

Performance of a refrigeration cycle is usually described by a **coefficient of performance (COP)**, defined as the benefit of the cycle (amount of heat removed) divided by the required energy input to operate the cycle:

$$\text{COP} \equiv \frac{\text{Useful refrigerating effect}}{\text{Net energy supplied from external sources}} \tag{7.1}$$

For a mechanical vapor compression system, the net energy supplied is usually in the form of work, mechanical or electrical, and may include work to the compressor and fans or pumps. Thus,

$$\text{COP} = \frac{Q_{evap}}{W_{net}} \tag{7.2}$$

In an absorption refrigeration cycle, the net energy supplied is usually in the form of heat into the generator and work into the pumps and fans, or

$$\text{COP} = \frac{Q_{evap}}{Q_{gen} + W_{net}} \tag{7.3}$$

In many cases, work supplied to an absorption system is very small compared to the amount of heat supplied to the generator, so the work term is often neglected.

Applying the second law to an entire refrigeration cycle shows that a completely reversible cycle operating under the same conditions has the maximum possible COP. Departure of the actual cycle from an ideal reversible cycle is given by the **refrigerating efficiency**:

$$\eta_R = \frac{\text{COP}}{(\text{COP})_{rev}} \tag{7.4}$$

Heat into evaporator ${}_4Q_1 = m(h_1 - h_4)$ kW
Work of compression ${}_1W_2 = m(h_2 - h_1)$ with s = constant kW
Heat out to condenser ${}_2Q_3 = m(h_2 - h_3)$ kW
Expansion by throttling flow $h_3 = h_4$

Coefficient of performance

$$\text{COP} = \frac{{}_4Q_1}{{}_1W_2} = \frac{h_1 - h_4}{h_2 - h_1} \tag{7.5}$$

where

m	=	refrigerant flow rate, kg/s
h	=	enthalpy, kJ/kg
s	=	entropy, kJ/kg·K

Theoretical compressor displacement, $D = m\, v_1$ m^3/s
where v_1 = specific volume at suction, m^3/kg.

For a given cycle, capacity in kW of refrigeration:

$$m = \frac{\text{kW}}{h_1 - h_4} \tag{7.6}$$

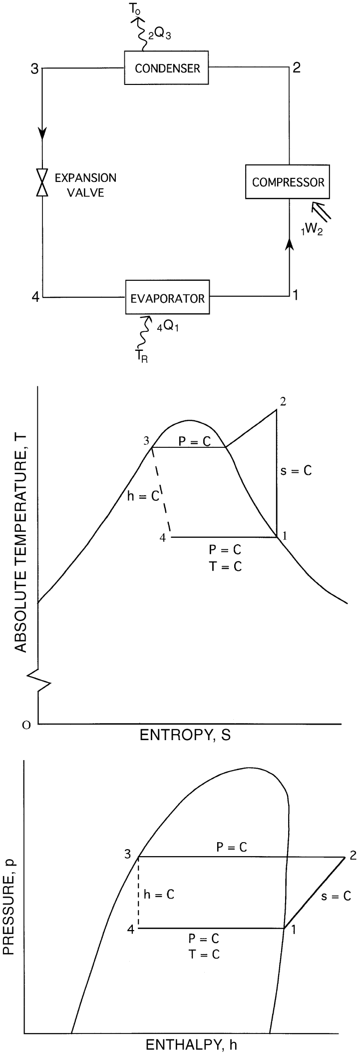


Figure 7.1 Theoretical Single-Stage Vapor Compression Refrigeration Cycle [2017F, Ch 2, Fig 8]

There are pressure drops in evaporator, condenser, and piping. There is power input to evaporator and condenser. There are heat gains and losses between refrigerant and environment. The liquid is subcooled; the suction vapor is superheated.

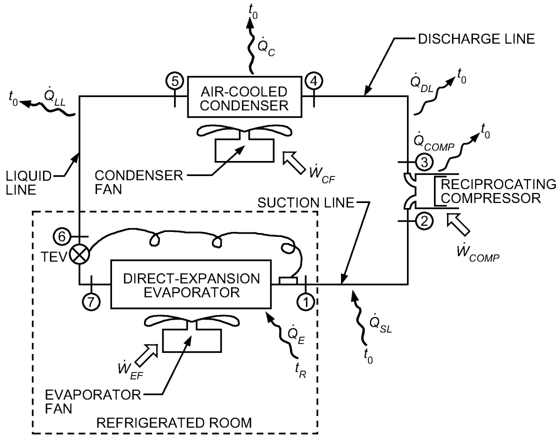


Figure 7.2 Schematic of Real, Direct-Expansion, Single-Stage Mechanical Vapor-Compression Refrigeration System [2017F, Ch 2, Fig 14]

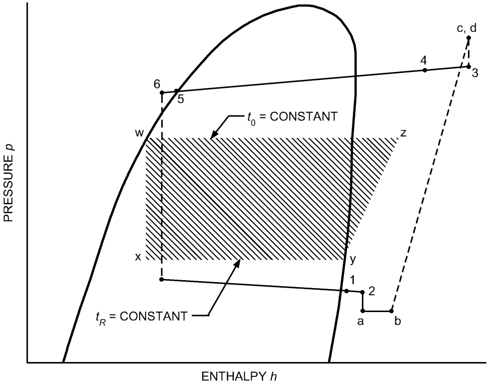


Figure 7.3 Pressure-Enthalpy Diagram of Actual System and Theoretical Single-Stage System Operating Between Same Inlet Air Temperatures t_R and t_0 [2017F, Ch 2, Fig 15]

8. REFRIGERANTS

Refrigerant Data

Table 8.1 Refrigerant Data and Safety Classifications
[2017F, Ch29, Tbl 1]

Refrigerant Number	Chemical Name[a,b]	Chemical Formula[a]	Molecular Mass[a]	Normal Boiling Point,[a] °C	Safety Group
Methane Series					
11	Trichlorofluoromethane	CCl_3F	137.4	24	A1
12	Dichlorodifluoromethane	CCl_2F_2	120.9	–30	A1
12B1	Bromochlorodifluoromethane	$CBrClF_2$	165.4	–4	
13	Chlorotrifluoromethane	$CClF_3$	104.5	–81	A1
13B1	Bromotrifluoromethane	$CBrF_3$	148.9	–58	A1
14	Tetrafluoromethane (carbon tetrafluoride)	CF_4	88.0	–128	A1
21	Dichlorofluoromethane	$CHCl_2F$	102.9	9	B1
22	Chlorodifluoromethane	$CHClF_2$	86.5	–41	A1
23	Trifluoromethane	CHF_3	70.0	–82	A1
30	Dichloromethane (methylene chloride)	CH_2Cl_2	84.9	40	B2
31	Chlorofluoromethane	CH_2ClF	68.5	–9	
32	Difluoromethane (methylene fluoride)	CH_2F_2	52.0	–52	A2L
40	Chloromethane (methyl chloride)	CH_3Cl	50.4	–24	B2
41	Fluoromethane (methyl fluoride)	CH_3F	34.0	–78	
50	Methane	CH_4	16.0	–161	A3
Ethane Series					
113	1,1,2-trichloro-1,2,2-trifluoroethane	CCl_2FCClF_2	187.4	48	A1
114	1,2-dichloro-1,1,2,2-tetrafluoroethane	$CClF_2CClF_2$	170.9	4	A1
115	Chloropentafluoroethane	$CClF_2CF_3$	154.5	–39	A1
116	Hexafluoroethane	CF_3CF_3	138.0	–78	A1
123	2,2-dichloro-1,1,1-trifluoroethane	$CHCl_2CF_3$	153.0	27	B1
124	2-chloro-1,1,1,2-tetrafluoroethane	$CHClFCF_3$	136.5	–12	A1
125	Pentafluoroethane	CHF_2CF_3	120.0	–48	A1
134a	1,1,1,2-tetrafluoroethane	CH_2FCF_3	102.0	–26	A1
141b	1,1-dichloro-1-fluoroethane	CH_3CCl_2F	117.0	32	
142b	1-chloro-1,1-difluoroethane	CH_3CClF_2	100.5	–10	A2
143a	1,1,1-trifluoroethane	CH_3CF_3	84.0	–47	A2L
152a	1,1-difluoroethane	CH_3CHF_2	66.0	–24	A2
170	Ethane	CH_3CH_3	30.0	–89	A3
Ethers					
E170	Dimethyl ether	CH_3OCH_3	46.0	–25	A3
Propane Series					
218	Octafluoropropane	$CF_3CF_2CF_3$	188.0	–37	A1
227ea	1,1,1,2,3,3,3-heptafluoropropane	CF_3CHFCF_3	170.0	–16	A1
236fa	1,1,1,3,3,3-hexafluoropropane	$CF_3CH_2CF_3$	152.0	–1	A1
245fa	1,1,1,3,3-pentafluoropropane	$CF_3CH_2CHF_2$	134.0	15	B1
290	Propane	$CH_3CH_2CH_3$	44.0	–42	A3
Cyclic Organic Compounds (see 2017F, Ch 29, Tbl 2 for blends)					
C318	Octafluorocyclobutane	$–(CF_2)_4–$	200.0	–6	A1

Table 8.1 Refrigerant Data and Safety Classifications
[2017F, Ch29, Tbl 1] (*Continued*)

Refrigerant Number	Chemical Name[a,b]	Chemical Formula[a]	Molecular Mass[a]	Normal Boiling Point,[a] °C	Safety Group
Miscellaneous Organic Compounds					
Hydrocarbons					
600	Butane	$CH_3CH_2CH_2CH_3$	58.1	0	A3
600a	2-methylpropane (isobutane)	$CH(CH_3)_2CH_3$	58.1	–12	A3
601	Pentane	$CH_3(CH_2)_3CH_3$	72.15	36.1	A3
601a	2-methylbutane (isopentane)	$(CH_3)_2CHCH_2CH_3$	72.15	27.8	A3
Oxygen Compounds					
610	Ethyl ether	$CH_3CH_2OCH_2CH_3$	74.1	35	
611	Methyl formate	$HCOOCH_3$	60.0	32	B2
Sulfur Compounds					
620	(Reserved for future assignment)				
Nitrogen Compounds					
630	Methanamine (methyl amine)	CH_3NH_2	31.1	–7	
631	Ethanamine (ethyl amine)	$CH_3CH_2(NH_2)$	45.1	17	
Inorganic Compounds					
702	Hydrogen	H_2	2.0	–253	A3
704	Helium	He	4.0	–269	A1
717	Ammonia	NH_3	17.0	–33	B2L
718	Water	H_2O	18.0	100	A1
720	Neon	Ne	20.2	–246	A1
728	Nitrogen	N_2	28.1	–196	A1
732	Oxygen	O_2	32.0	–183	
740	Argon	Ar	39.9	–186	A1
744	Carbon dioxide	CO_2	44.0	–78[c]	A1
744A	Nitrous oxide	N_2O	44.0	–90	
764	Sulfur dioxide	SO_2	64.1	–10	B1
Unsaturated Organic Compounds					
1150	Ethene (ethylene)	$CH_2=CH_2$	28.1	–104	A3
1233zd(E)	Trans-1-chloro-3,3,3-trifluoro-1-propene	$CF_3CH=CHCl$	130.5	18	A1
1234yf	2,3,3,3-tetrafluoro-1-propene	$CF_3CF=CH_2$	114.0	–29.4	A2L
1234ze(E)	Trans-1,3,3,3-tetrafluoro-1-propene	$CF_3CH=CHF$	114.0	–19.0	A2L
1270	Propene (propylene)	$CH_3CH=CH_2$	42.1	–48	A3
1336mzz(Z)	Cis-1,1,1,4,4,4-hexafluoro-2-butene	$CF_3CH=CHCF_3$	164.1	33	A1

Source: ANSI/ASHRAE *Standard* 34-2010.
[a]Chemical name, chemical formula, molecular mass, and normal boiling point are not part of this standard.
[b]Preferred chemical name is followed by the popular name in parentheses.
[c]Sublimes.

The environmental effect of the chlorine in CFCs and HCFCs has resulted in CFCs no longer being manufactured and the manufacture of HCFCs being phased out.

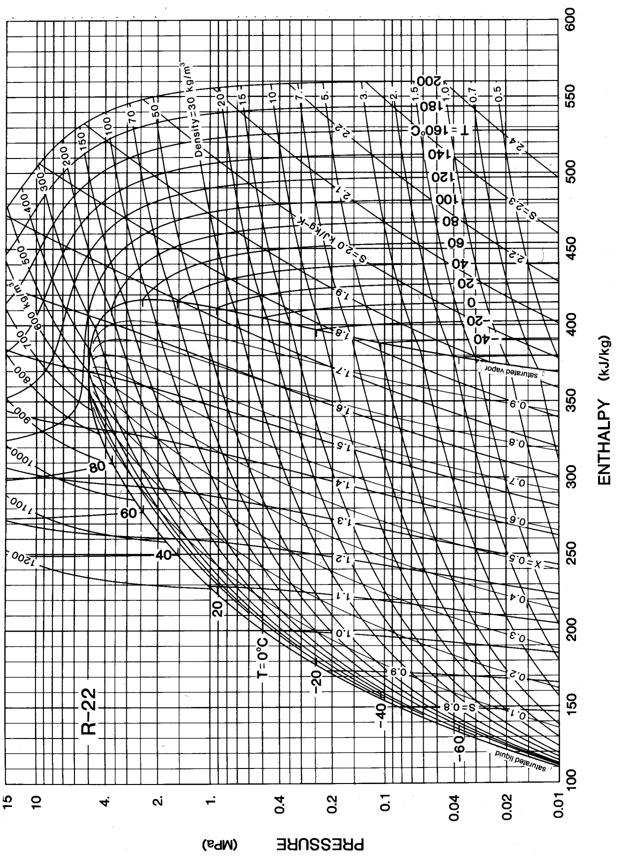


Figure 8.1 Refrigerant 22 (Chlorodifluoromethane) Properties of Saturated Liquid and Saturated Vapor
[2017F, Ch 30, Fig 2]

Table 8.2 R-22 (Chlorodifluoromethane) Properties of Saturated Liquid and Saturated Vapor [2017F, Ch 30, Tbl R-22]

Temp.,* °C	Pressure, MPa	Density, kg/m^3 Liquid	Volume, m^3/kg Vapor	Enthalpy, kJ/kg Liquid	Enthalpy, kJ/kg Vapor	Entropy, kJ/(kg·K) Liquid	Entropy, kJ/(kg·K) Vapor
–100	0.00201	1571.3	8.26600	90.71	358.97	0.5050	2.0543
–90	0.00481	1544.9	3.64480	101.32	363.85	0.5646	1.9980
–80	0.01037	1518.2	1.77820	111.94	368.77	0.6210	1.9508
–70	0.02047	1491.2	0.94342	122.58	373.70	0.6747	1.9108
–60	0.03750	1463.7	0.53680	133.27	378.59	0.7260	1.8770
–50	0.06453	1435.6	0.32385	144.03	383.42	0.7752	1.8480
–48	0.07145	1429.9	0.29453	146.19	384.37	0.7849	1.8428
–46	0.07894	1424.2	0.26837	148.36	385.32	0.7944	1.8376
–44	0.08705	1418.4	0.24498	150.53	386.26	0.8039	1.8327
–42	0.09580	1412.6	0.22402	152.70	387.20	0.8134	1.8278
–40.81[b]	0.10132	1409.2	0.21260	154.00	387.75	0.8189	1.8250
–40	0.10523	1406.8	0.20521	154.89	388.13	0.8227	1.8231
–38	0.11538	1401.0	0.18829	157.07	389.06	0.8320	1.8186
–36	0.12628	1395.1	0.17304	159.27	389.97	0.8413	1.8141
–34	0.13797	1389.1	0.15927	161.47	390.89	0.8505	1.8098
–32	0.15050	1383.2	0.14682	163.67	391.79	0.8596	1.8056
–30	0.16389	1377.2	0.13553	165.88	392.69	0.8687	1.8015
–28	0.17819	1371.1	0.12528	168.10	393.58	0.8778	1.7975
–26	0.19344	1365.0	0.11597	170.33	394.47	0.8868	1.7937
–24	0.20968	1358.9	0.10749	172.56	395.34	0.8957	1.7899
–22	0.22696	1352.7	0.09975	174.80	396.21	0.9046	1.7862
–20	0.24531	1346.5	0.09268	177.04	397.06	0.9135	1.7826
–18	0.26479	1340.3	0.08621	179.30	397.91	0.9223	1.7791
–16	0.28543	1334.0	0.08029	181.56	398.75	0.9311	1.7757
–14	0.30728	1327.6	0.07485	183.83	399.57	0.9398	1.7723
–12	0.33038	1321.2	0.06986	186.11	400.39	0.9485	1.7690
–10	0.35479	1314.7	0.06527	188.40	401.20	0.9572	1.7658
–8	0.38054	1308.2	0.06103	190.70	401.99	0.9658	1.7627
–6	0.40769	1301.6	0.05713	193.01	402.77	0.9744	1.7596
–4	0.43628	1295.0	0.05352	195.33	403.55	0.9830	1.7566
–2	0.46636	1288.3	0.05019	197.66	404.30	0.9915	1.7536
0	0.49799	1281.5	0.04710	200.00	405.05	1.0000	1.7507
2	0.53120	1274.7	0.04424	202.35	405.78	1.0085	1.7478
4	0.56605	1267.8	0.04159	204.71	406.50	1.0169	1.7450
6	0.60259	1260.8	0.03913	207.09	407.20	1.0254	1.7422
8	0.64088	1253.8	0.03683	209.47	407.89	1.0338	1.7395
10	0.68095	1246.7	0.03470	211.87	408.56	1.0422	1.7368
12	0.72286	1239.5	0.03271	214.28	409.21	1.0505	1.7341
14	0.76668	1232.2	0.03086	216.70	409.85	1.0589	1.7315
16	0.81244	1224.9	0.02912	219.14	410.47	1.0672	1.7289
18	0.86020	1217.4	0.02750	221.59	411.07	1.0755	1.7263
20	0.91002	1209.9	0.02599	224.06	411.66	1.0838	1.7238
22	0.96195	1202.3	0.02457	226.54	412.22	1.0921	1.7212
24	1.01600	1194.6	0.02324	229.04	412.77	1.1004	1.7187
26	1.07240	1186.7	0.02199	231.55	413.29	1.1086	1.7162
28	1.13090	1178.8	0.02082	234.08	413.79	1.1169	1.7136
30	1.19190	1170.7	0.01972	236.62	414.26	1.1252	1.7111
32	1.25520	1162.6	0.01869	239.19	414.71	1.1334	1.7086
34	1.32100	1154.3	0.01771	241.77	415.14	1.1417	1.7061
36	1.38920	1145.8	0.01679	244.38	415.54	1.1499	1.7036
38	1.46010	1137.3	0.01593	247.00	415.91	1.1582	1.7010
40	1.53360	1128.5	0.01511	249.65	416.25	1.1665	1.6985
42	1.60980	1119.6	0.01433	252.32	416.55	1.1747	1.6959
44	1.68870	1110.6	0.01360	255.01	416.83	1.1830	1.6933
46	1.77040	1101.4	0.01291	257.73	417.07	1.1913	1.6906
48	1.85510	1091.9	0.01226	260.47	417.27	1.1997	1.6879
50	1.94270	1082.3	0.01163	263.25	417.44	1.2080	1.6852
52	2.03330	1072.4	0.01104	266.05	417.56	1.2164	1.6824
54	2.12700	1062.3	0.01048	268.89	417.63	1.2248	1.6795
56	2.22390	1052.0	0.00995	271.76	417.66	1.2333	1.6766
58	2.32400	1041.3	0.00944	274.66	417.63	1.2418	1.6736
60	2.42750	1030.4	0.00896	277.61	417.55	1.2504	1.6705
65	2.70120	1001.4	0.00785	285.18	417.06	1.2722	1.6622
70	2.99740	969.7	0.00685	293.10	416.09	1.2945	1.6529
75	3.31770	934.4	0.00595	301.46	414.49	1.3177	1.6424
80	3.66380	893.7	0.00512	310.44	412.01	1.3423	1.6299
85	4.03780	844.8	0.00434	320.38	408.19	1.3690	1.6142
90	4.44230	780.1	0.00356	332.09	401.87	1.4001	1.5922
95	4.88240	662.9	0.00262	349.56	387.28	1.4462	1.5486
96.15[c]	4.99000	523.8	0.00191	366.90	366.90	1.4927	1.4927

*Temperatures on ITS-90 scale [b]Normal boiling point [c]Critical point

Table 8.3 Superheated Vapor Thermodynamic Properties of R-22

Temp., °C	Pressure = 200 kPa Sat. Temp. = –25.20°C			Pressure = 400 kPa Sat. Temp. = –6.57°C		
	ρ	***h***	***s***	ρ	***h***	***s***
–20	8.647	243.8	0.9847			
–10	8.267	250.0	1.009			
0	7.923	256.3	1.032	16.56	252.9	0.9569
10	7.609	262.8	1.056	15.82	259.5	0.9809
20	7.321	269.3	1.078	15.15	266.3	1.004
40	6.810	282.7	1.122	13.99	280.1	1.050
60	6.370	296.4	1.165	13.01	294.1	1.093
Temp., °C	**Pressure = 500 kPa Sat. Temp. = 0.11°C**			**Pressure = 600 kPa Sat. Temp. = 5.84°C**		
10	20.19	257.8	0.9552	24.77	265.1	0.9332
20	19.28	264.7	0.9791	23.58	263.1	0.9576
30	19.46	271.7	1.002	22.53	270.2	0.9814
40	17.73	278.7	1.025	21.58	277.3	1.005
50	17.06	285.8	1.048	20.73	284.5	1.027
60	16.44	293.0	1.069	19.95	291.8	1.049
70	15.87	300.2	1.091	19.24	299.1	1.071
Temp., °C	**Pressure = 800 kPa Sat. Temp. = 15.44°C**			**Pressure = 1000 kPa Sat. Temp. = 23.38°C**		
20	32.77	259.7	0.9214			
40	29.67	274.5	0.9702	38.34	271.4	0.9416
60	27.23	289.3	1.016	34.89	286.8	0.9891
80	25.24	304.4	1.060	32.15	302.2	1.034
100	23.57	319.8	1.102	29.90	317.9	1.077
120	22.14	335.4	1.143	28.00	333.7	1.119
140	20.89	351.3	1.183	26.37	349.9	1.159
Temp., °C	**Pressure = 1200 kPa Sat. Temp. = 30.21°C**			**Pressure = 1400 kPa Sat. Temp. = 36.25°C**		
40	47.73	268.2	0.9163	58.00	364.7	0.8930
60	43.00	284.1	0.9657	51.61	281.3	0.9445
80	39.36	300.0	1.012	46.90	297.7	0.9922
100	36.44	315.9	1.056	43.20	314.0	1.037
120	34.02	332.1	1.098	40.19	330.4	1.080
140	31.96	348.4	1.138	37.66	346.9	1.121
160	30.18	365.0	1.178	35.49	363.7	1.161
Temp., °C	**Pressure = 1600 kPa Sat. Temp. = 41.69°C**			**Pressure = 1800 kPa Sat. Temp. = 46.65°C**		
60	60.82	278.4	0.9249	70.76	275.2	0.9064
80	54.80	295.3	0.9742	63.11	292.8	0.9575
100	50.20	311.9	1.020	57.47	309.9	1.005
120	46.53	328.6	1.064	53.04	326.9	1.049
140	43.48	345.4	1.105	49.43	343.9	1.091
160	40.90	362.4	1.146	46.40	361.1	1.132

ρ = vapor density, kg/m^3; *h* = enthalpy, kJ/kg; *s* = entropy, kJ/(kg· K)

Refrigerants

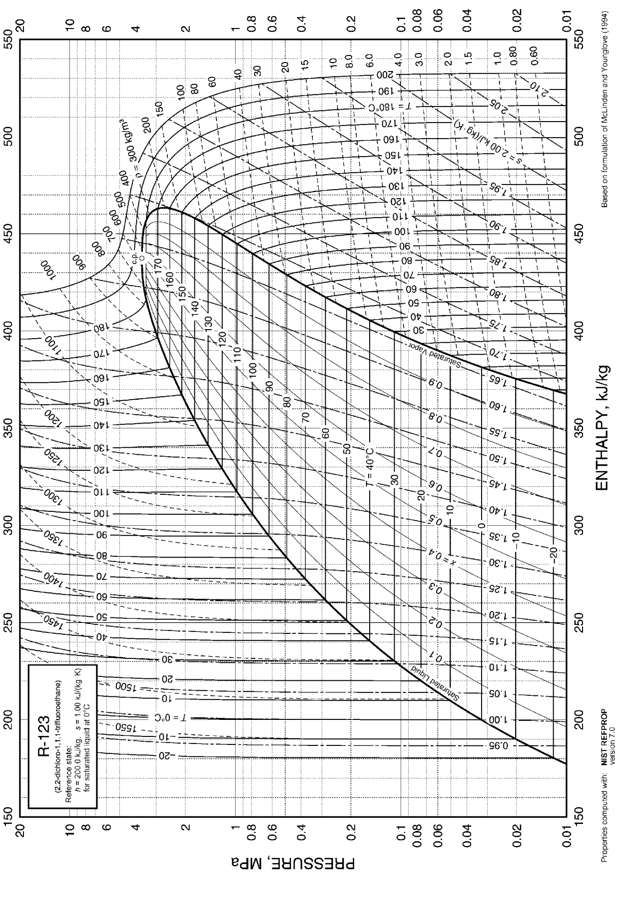


Figure 8.2 Pressure-Enthalpy Diagram for Refrigerant 123 [2017F, Ch 30, Fig 5]

Table 8.4 R-123 (2,2-Dichloro-1,1,1-Trifluoroethane) Properties of Saturated Liquid and Saturated Vapor [2017F, Ch 30, Tbl R-123]

Temp.,* °C	Pressure, MPa	Density, kg/m^3 Liquid	Volume, m^3/kg Vapor	Enthalpy, kJ/kg Liquid	Enthalpy, kJ/kg Vapor	Entropy, kJ/(kg·K) Liquid	Entropy, kJ/(kg·K) Vapor	c_p/c_v Vapor
–80	0.00013	1709.6	83.6670	123.92	335.98	0.6712	1.7691	1.117
–70	0.00034	1687.4	32.8420	133.17	341.25	0.7179	1.7422	1.113
–60	0.00081	1665.1	14.3330	142.46	346.66	0.7625	1.7206	1.110
–50	0.00177	1642.6	6.84600	151.81	352.21	0.8054	1.7034	1.107
–40	0.00358	1620.0	3.53190	161.25	357.88	0.8468	1.6901	1.105
–30	0.00675	1597.0	1.94700	170.78	363.65	0.8868	1.6800	1.103
–20	0.01200	1573.8	1.13640	180.41	369.52	0.9256	1.6726	1.102
–10	0.02025	1550.1	0.69690	190.15	375.45	0.9633	1.6675	1.102
0	0.03265	1526.1	0.44609	200.00	381.44	1.0000	1.6642	1.102
2	0.03574	1521.3	0.40991	201.98	382.64	1.0072	1.6638	1.103
4	0.03907	1516.4	0.37720	203.97	383.84	1.0144	1.6634	1.103
6	0.04264	1511.5	0.34759	205.97	385.05	1.0216	1.6631	1.103
8	0.04647	1506.6	0.32075	207.96	386.25	1.0287	1.6628	1.103
10	0.05057	1501.6	0.29637	209.97	387.46	1.0358	1.6626	1.104
12	0.05495	1496.7	0.27420	211.97	388.66	1.0428	1.6625	1.104
14	0.05963	1491.7	0.25401	213.99	389.87	1.0499	1.6624	1.104
16	0.06463	1486.7	0.23559	216.00	391.08	1.0569	1.6623	1.105
18	0.06995	1481.7	0.21877	218.02	392.29	1.0638	1.6623	1.105
20	0.07561	1476.6	0.20338	220.05	393.49	1.0707	1.6624	1.106
22	0.08163	1471.5	0.18929	222.08	394.70	1.0776	1.6625	1.106
24	0.08802	1466.4	0.17637	224.12	395.91	1.0845	1.6626	1.107
26	0.09480	1461.3	0.16451	226.16	397.12	1.0913	1.6628	1.107
27.82[b]	0.10133	1456.6	0.15453	228.03	398.22	1.0975	1.6630	1.108
28	0.10198	1456.2	0.15360	228.21	398.32	1.0981	1.6630	1.108
30	0.10958	1451.0	0.14356	230.26	399.53	1.1049	1.6633	1.109
32	0.11762	1445.8	0.13431	232.31	400.73	1.1116	1.6635	1.109
34	0.12611	1440.6	0.12577	234.38	401.93	1.1183	1.6639	1.110
36	0.13507	1435.4	0.11789	236.44	403.14	1.1250	1.6642	1.111
38	0.14452	1430.1	0.11060	238.51	404.34	1.1317	1.6646	1.112
40	0.15447	1424.8	0.10385	240.59	405.54	1.1383	1.6651	1.113
42	0.16495	1419.4	0.09759	242.67	406.73	1.1449	1.6655	1.114
44	0.17597	1414.1	0.09179	244.76	407.93	1.1515	1.6660	1.115
46	0.18755	1408.7	0.08641	246.86	409.12	1.1581	1.6665	1.116
48	0.19971	1403.3	0.08140	248.95	410.31	1.1646	1.6670	1.117
50	0.21246	1397.8	0.07674	251.06	411.50	1.1711	1.6676	1.119
52	0.22584	1392.3	0.07240	253.17	412.69	1.1776	1.6682	1.120
54	0.23985	1386.8	0.06836	255.28	413.87	1.1840	1.6688	1.121
56	0.25451	1381.2	0.06458	257.41	415.05	1.1905	1.6694	1.123
58	0.26985	1375.6	0.06106	259.53	416.23	1.1969	1.6701	1.124
60	0.28589	1370.0	0.05777	261.67	417.40	1.2033	1.6707	1.126
62	0.30264	1364.3	0.05469	263.81	418.57	1.2096	1.6714	1.127
64	0.32013	1358.6	0.05180	265.95	419.73	1.2160	1.6721	1.129
66	0.33838	1352.8	0.04910	268.10	420.89	1.2223	1.6728	1.131
68	0.35740	1347.0	0.04656	270.26	422.05	1.2286	1.6735	1.133
70	0.37722	1341.2	0.04418	272.42	423.20	1.2349	1.6743	1.135
72	0.39787	1335.3	0.04195	274.60	424.35	1.2411	1.6750	1.137
74	0.41936	1329.3	0.03985	276.77	425.50	1.2474	1.6758	1.139
76	0.44171	1323.4	0.03787	278.96	426.63	1.2536	1.6766	1.142
78	0.46494	1317.3	0.03601	281.15	427.77	1.2598	1.6774	1.144
80	0.48909	1311.2	0.03426	283.35	428.89	1.2660	1.6781	1.147
82	0.51416	1305.1	0.03261	285.55	430.01	1.2722	1.6789	1.150
84	0.54019	1298.9	0.03105	287.77	431.13	1.2783	1.6797	1.152
86	0.56720	1292.6	0.02958	289.99	432.23	1.2845	1.6806	1.156
88	0.59520	1286.3	0.02819	292.22	433.33	1.2906	1.6814	1.159
90	0.62423	1279.9	0.02687	294.45	434.43	1.2967	1.6822	1.162
92	0.65430	1273.5	0.02563	296.70	435.51	1.3028	1.6830	1.166
94	0.68544	1266.9	0.02445	298.95	436.59	1.3089	1.6838	1.169
96	0.71768	1260.3	0.02334	301.21	437.66	1.3150	1.6846	1.173
98	0.75103	1253.7	0.02228	303.49	438.72	1.3211	1.6854	1.177
100	0.78553	1246.9	0.02128	305.77	439.77	1.3271	1.6862	1.182
110	0.97603	1211.9	0.01697	317.32	444.88	1.3572	1.6902	1.208
120	1.19900	1174.4	0.01361	329.15	449.67	1.3872	1.6938	1.243
130	1.45780	1133.6	0.01094	341.32	454.07	1.4173	1.6969	1.294
140	1.75630	1088.3	0.00879	353.92	457.94	1.4475	1.6992	1.369
150	2.09870	1036.8	0.00703	367.10	461.05	1.4782	1.7003	1.493
160	2.49010	975.7	0.00555	381.13	463.01	1.5101	1.6991	1.726
170	2.93720	896.9	0.00425	396.61	462.89	1.5443	1.6939	2.309
180	3.45060	765.9	0.00292	416.22	456.82	1.5867	1.6763	6.158
183.68[c]	3.66180	550.0	0.00182	437.39	437.39	1.6325	1.6325	∞

*Temperatures on ITS-90 scale   [b]Normal boiling point   [c]Critical point

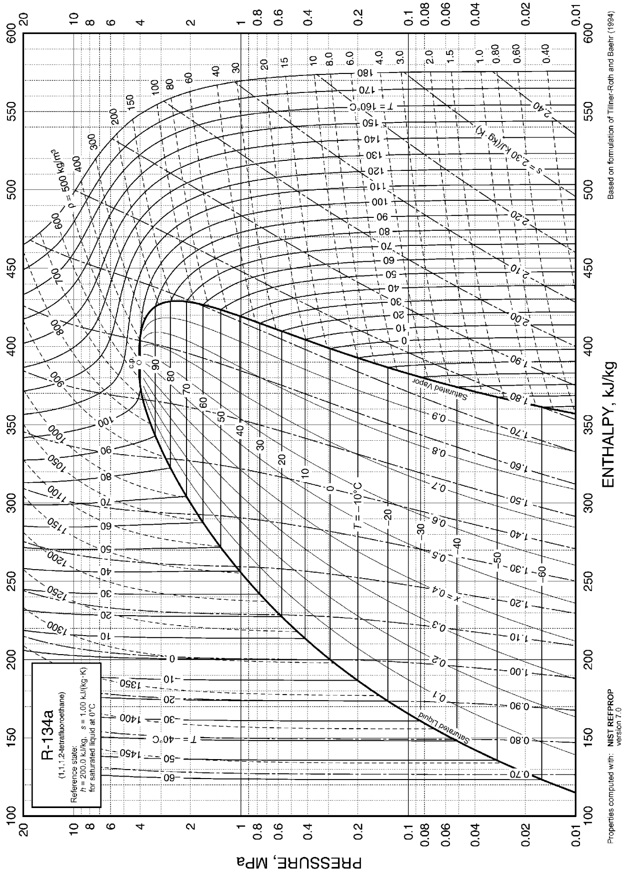


Figure 8.3 Pressure-Enthalpy Diagram for Refrigerant 134a [2017F, Ch 30, Fig 8]

Table 8.5 R-134a (1,1,1,2-Tetrafluoroethane) Properties of Saturated Liquid and Saturated Vapor
[2017F, Ch 30, Tbl R-134a]

Temp.,* °C	Pressure, MPa	Density, kg/m^3 Liquid	Volume, m^3/kg Vapor	Enthalpy, kJ/kg Liquid	Enthalpy, kJ/kg Vapor	Entropy, kJ/(kg·K) Liquid	Entropy, kJ/(kg·K) Vapor	c_p/c_v Vapor
–103.30[a]	0.00039	1591.1	35.4960	71.46	334.94	0.4126	1.9639	1.164
–100	0.00056	1582.4	25.1930	75.36	336.85	0.4354	1.9456	1.162
–90	0.00152	1555.8	9.7698	87.23	342.76	0.5020	1.8972	1.156
–80	0.00367	1529.0	4.2682	99.16	348.83	0.5654	1.8580	1.151
–70	0.00798	1501.9	2.0590	111.20	355.02	0.6262	1.8264	1.148
–60	0.01591	1474.3	1.0790	123.36	361.31	0.6846	1.8010	1.146
–50	0.02945	1446.3	0.60620	135.67	367.65	0.7410	1.7806	1.146
–40	0.05121	1417.7	0.36108	148.14	374.00	0.7956	1.7643	1.148
–30	0.08438	1388.4	0.22594	160.79	380.32	0.8486	1.7515	1.152
–28	0.09270	1382.4	0.20680	163.34	381.57	0.8591	1.7492	1.153
–26.07[b]	0.10133	1376.7	0.19018	165.81	382.78	0.8690	1.7472	1.154
–26	0.10167	1376.5	0.18958	165.90	382.82	0.8694	1.7471	1.154
–24	0.11130	1370.4	0.17407	168.47	384.07	0.8798	1.7451	1.155
–22	0.12165	1364.4	0.16006	171.05	385.32	0.8900	1.7432	1.156
–20	0.13273	1358.3	0.14739	173.64	386.55	0.9002	1.7413	1.158
–18	0.14460	1352.1	0.13592	176.23	387.79	0.9104	1.7396	1.159
–16	0.15728	1345.9	0.12551	178.83	389.02	0.9205	1.7379	1.161
–14	0.17082	1339.7	0.11605	181.44	390.24	0.9306	1.7363	1.163
–12	0.18524	1333.4	0.10744	184.07	391.46	0.9407	1.7348	1.165
–10	0.20060	1327.1	0.09959	186.70	392.66	0.9506	1.7334	1.167
–8	0.21693	1320.8	0.09242	189.34	393.87	0.9606	1.7320	1.169
–6	0.23428	1314.3	0.08587	191.99	395.06	0.9705	1.7307	1.171
–4	0.25268	1307.9	0.07987	194.65	396.25	0.9804	1.7294	1.174
–2	0.27217	1301.4	0.07436	197.32	397.43	0.9902	1.7282	1.176
0	0.29280	1294.8	0.06931	200.00	398.60	1.0000	1.7271	1.179
2	0.31462	1288.1	0.06466	202.69	399.77	1.0098	1.7260	1.182
4	0.33766	1281.4	0.06039	205.40	400.92	1.0195	1.7250	1.185
6	0.36198	1274.7	0.05644	208.11	402.06	1.0292	1.7240	1.189
8	0.38761	1267.9	0.05280	210.84	403.20	1.0388	1.7230	1.192
10	0.41461	1261.0	0.04944	213.58	404.32	1.0485	1.7221	1.196
12	0.44301	1254.0	0.04633	216.33	405.43	1.0581	1.7212	1.200
14	0.47288	1246.9	0.04345	219.09	406.53	1.0677	1.7204	1.204
16	0.50425	1239.8	0.04078	221.87	407.61	1.0772	1.7196	1.209
18	0.53718	1232.6	0.03830	224.66	408.69	1.0867	1.7188	1.214
20	0.57171	1225.3	0.03600	227.47	409.75	1.0962	1.7180	1.219
22	0.60789	1218.0	0.03385	230.29	410.79	1.1057	1.7173	1.224
24	0.64578	1210.5	0.03186	233.12	411.82	1.1152	1.7166	1.230
26	0.68543	1202.9	0.03000	235.97	412.84	1.1246	1.7159	1.236
28	0.72688	1195.2	0.02826	238.84	413.84	1.1341	1.7152	1.243
30	0.77020	1187.5	0.02664	241.72	414.82	1.1435	1.7145	1.249
32	0.81543	1179.6	0.02513	244.62	415.78	1.1529	1.7138	1.257
34	0.86263	1171.6	0.02371	247.54	416.72	1.1623	1.7131	1.265
36	0.91185	1163.4	0.02238	250.48	417.65	1.1717	1.7124	1.273
38	0.96315	1155.1	0.02113	253.43	418.55	1.1811	1.7118	1.282
40	1.0166	1146.7	0.01997	256.41	419.43	1.1905	1.7111	1.292
42	1.0722	1138.2	0.01887	259.41	420.28	1.1999	1.7103	1.303
44	1.1301	1129.5	0.01784	262.43	421.11	1.2092	1.7096	1.314
46	1.1903	1120.6	0.01687	265.47	421.92	1.2186	1.7089	1.326
48	1.2529	1111.5	0.01595	268.53	422.69	1.2280	1.7081	1.339
50	1.3179	1102.3	0.01509	271.62	423.44	1.2375	1.7072	1.354
52	1.3854	1092.9	0.01428	274.74	424.15	1.2469	1.7064	1.369
54	1.4555	1083.2	0.01351	277.89	424.83	1.2563	1.7055	1.386
56	1.5282	1073.4	0.01278	281.06	425.47	1.2658	1.7045	1.405
58	1.6036	1063.2	0.01209	284.27	426.07	1.2753	1.7035	1.425
60	1.6818	1052.9	0.01144	287.50	426.63	1.2848	1.7024	1.448
62	1.7628	1042.2	0.01083	290.78	427.14	1.2944	1.7013	1.473
64	1.8467	1031.2	0.01024	294.09	427.61	1.3040	1.7000	1.501
66	1.9337	1020.0	0.00969	297.44	428.02	1.3137	1.6987	1.532
68	2.0237	1008.3	0.00916	300.84	428.36	1.3234	1.6972	1.567
70	2.1168	996.2	0.00865	304.28	428.65	1.3332	1.6956	1.607
72	2.2132	983.8	0.00817	307.78	428.86	1.3430	1.6939	1.653
74	2.3130	970.8	0.00771	311.33	429.00	1.3530	1.6920	1.705
76	2.4161	957.3	0.00727	314.94	429.04	1.3631	1.6899	1.766
78	2.5228	943.1	0.00685	318.63	428.98	1.3733	1.6876	1.838
80	2.6332	928.2	0.00645	322.39	428.81	1.3836	1.6850	1.924
85	2.9258	887.2	0.00550	332.22	427.76	1.4104	1.6771	2.232
90	3.2442	837.8	0.00461	342.93	425.42	1.4390	1.6662	2.820
95	3.5912	772.7	0.00374	355.25	420.67	1.4715	1.6492	4.369
100	3.9724	651.2	0.00268	373.30	407.68	1.5188	1.6109	20.81
101.06[c]	4.0593	511.9	0.00195	389.64	389.64	1.5621	1.5621	∞

*Temperatures on ITS-90 scale [a] Triple point [b] Normal boiling point [c] Critical point

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Table 8.6 Superheated Vapor Thermodynamic Properties of R-134a

Temp, °C	Pressure = 0.101325 MPa Sat. temp. = –26.07°C			Pressure = 0.200 MPa Sat. temp. = –10.07°C		
	V	*h*	*s*	*V*	*h*	*s*
–20.00	5.11	387.68	1.7667	–10.00	10.01	392.77
–10.00	4.89	395.65	1.7976	0.00	9.54	401.21
0.00	4.69	403.74	1.8278	10.00	9.13	409.73
10.00	4.50	411.97	1.8574	20.00	8.76	418.35
20.00	4.34	420.34	1.8864	30.00	8.42	427.07
30.00	4.18	428.85	1.9150	40.00	8.12	435.90
40.00	4.04	437.52	1.9431	50.00	7.83	444.87
50.00	3.91	446.33	1.9708	60.00	7.57	453.97
60.00	3.78	455.30	1.9981			

Temp, °C	Pressure = 0.400 MPa Sat. temp. = 8.94°C			Pressure = 1.000 MPa Sat. temp. = 39.39°C		
	V	*h*	*s*	*V*	*h*	*s*
10.00	19.41	404.78	1.7263	70.00	41.21	452.05
20.00	18.45	414.00	1.7583	80.00	39.36	462.47
30.00	17.61	423.21	1.7892	90.00	37.74	472.86
40.00	16.87	432.46	1.8192	100.00	36.29	483.26
50.00	16.20	441.76	1.8485	110.00	34.99	493.69
60.00	15.60	451.15	1.8771	120.00	33.80	504.19
				130.00	32.71	514.75

Temp, °C	Pressure = 1.400 MPa Sat. temp. = 52.43°C			Pressure = 1.600 MPa Sat. temp. = 57.91°C		
	V	*h*	*s*	*V*	*h*	*s*
60.00	66.61	433.69	1.7347	60.00	80.74	428.99
70.00	62.25	445.31	1.7691	70.00	74.43	441.47
80.00	58.74	456.56	1.8014	80.00	69.61	453.30
90.00	55.79	467.60	1.8322	90.00	65.71	464.76
100.00	53.24	478.53	1.8619	100.00	62.43	476.01
110.00	51.03	489.39	1.8906	110.00	59.62	487.13
120.00	49.05	500.25	1.9186	120.00	57.14	498.19
130.00	47.28	511.11	1.9459	130.00	54.95	509.23

Temp, °C	Pressure = 2.000 MPa Sat. temp. = 67.49°C		
	V	*h*	*s*
70.00	104.37	432.22	1.7091
80.00	94.85	445.86	1.7483
90.00	87.97	458.49	1.7835
100.00	82.58	470.57	1.8164
110.00	78.17	482.32	1.8474
120.00	74.44	493.86	1.8772
130.00	71.18	505.30	1.9059
140.00	68.33	516.68	1.9338

V = vapor volume, kg/m^3
h = enthalpy, kJ/kg
s = entropy, kJ/kg·K

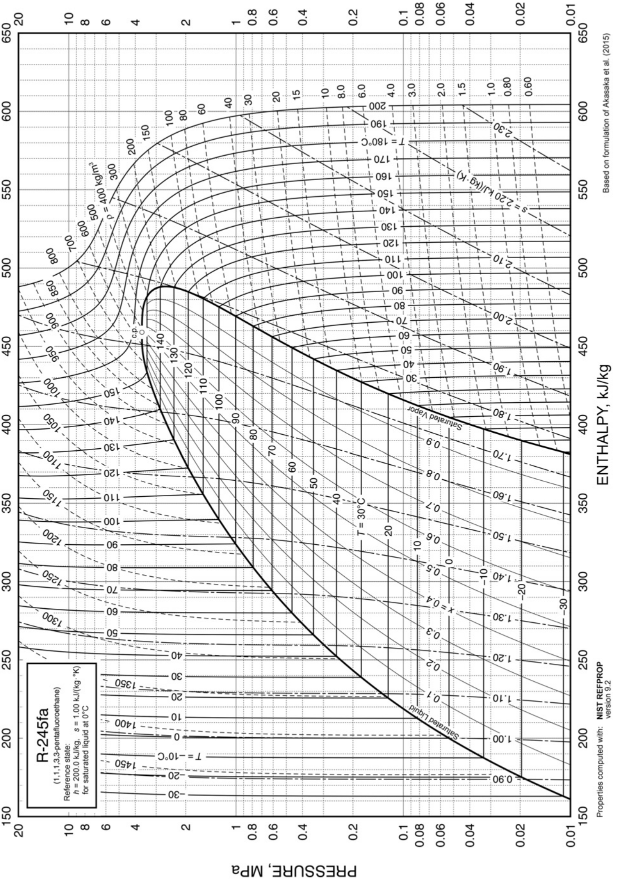


Figure 8.4 Pressure-Enthalpy Diagram for Refrigerant 245fa ([2017F, Ch 30, Fig 11]

Table 8.7 Refrigerant 245fa (1,1,1,3,3-pentafluoroethane) Properties of Saturated Liquid and Saturated Vapor [2017F, Ch 30, Tbl R-245fa]

Temp., °C	Pressure, MPa	Density, kg/m^3	Volume, m^3/kg	Enthalpy, kJ/kg		Entropy, kJ/(kg·K)		Specific Heat c_p, kJ/(kg·K)		c_p/c_v
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor
–60	0.00131	1548.2	10.041	127.42	361.18	0.7006	1.7973	1.166	0.695	1.099
–50	0.00289	1525.0	4.7815	139.14	368.14	0.7543	1.7805	1.178	0.716	1.097
–40	0.00584	1501.5	2.4619	150.99	375.25	0.8063	1.7681	1.192	0.738	1.095
–30	0.01103	1477.7	1.3552	162.99	382.49	0.8566	1.7594	1.207	0.760	1.094
–20	0.01961	1453.5	0.79014	175.14	389.83	0.9056	1.7537	1.224	0.783	1.093
–10	0.03307	1429.0	0.48405	187.48	397.25	0.9533	1.7505	1.242	0.807	1.094
0	0.05327	1403.9	0.30947	200.00	404.72	1.0000	1.7495	1.261	0.833	1.095
2	0.05831	1398.8	0.28429	202.53	406.22	1.0092	1.7495	1.265	0.838	1.096
4	0.06372	1393.7	0.26153	205.07	407.72	1.0184	1.7496	1.270	0.843	1.096
6	0.06953	1388.6	0.24093	207.61	409.22	1.0275	1.7497	1.274	0.849	1.097
8	0.07576	1383.4	0.22226	210.17	410.72	1.0366	1.7500	1.278	0.854	1.097
10	0.08242	1378.3	0.20530	212.73	412.22	1.0457	1.7502	1.282	0.860	1.098
12	0.08954	1373.0	0.18987	215.30	413.72	1.0547	1.7506	1.287	0.865	1.098
14	0.09714	1367.8	0.17582	217.88	415.22	1.0637	1.7510	1.291	0.871	1.099
15.05[b]	0.10132	1365.1	0.16896	219.24	416.01	1.0684	1.7512	1.293	0.874	1.100
16	0.10525	1362.5	0.16301	220.47	416.72	1.0727	1.7514	1.296	0.877	1.100
18	0.11388	1357.2	0.15131	223.07	418.22	1.0816	1.7519	1.300	0.883	1.101
20	0.12306	1351.9	0.14061	225.68	419.72	1.0905	1.7524	1.305	0.888	1.102
22	0.13282	1346.6	0.13080	228.29	421.22	1.0994	1.7530	1.309	0.894	1.102
24	0.14317	1341.2	0.12182	230.92	422.71	1.1082	1.7537	1.314	0.900	1.103
26	0.15415	1335.7	0.11356	233.56	424.21	1.1170	1.7544	1.319	0.907	1.104
28	0.16578	1330.3	0.10598	236.20	425.70	1.1258	1.7551	1.324	0.913	1.106
30	0.17808	1324.8	0.09899	238.86	427.19	1.1346	1.7559	1.329	0.919	1.107
32	0.19108	1319.3	0.09256	241.52	428.68	1.1433	1.7567	1.334	0.926	1.108
34	0.20481	1313.7	0.08662	244.20	430.17	1.1520	1.7575	1.339	0.932	1.109
36	0.21930	1308.1	0.08113	246.89	431.65	1.1607	1.7584	1.344	0.939	1.111
38	0.23457	1302.4	0.07606	249.58	433.13	1.1694	1.7593	1.349	0.946	1.112
40	0.25065	1296.7	0.07137	252.29	434.61	1.1780	1.7602	1.355	0.952	1.114
42	0.26757	1291.0	0.06702	255.01	436.08	1.1866	1.7612	1.360	0.959	1.115
44	0.28535	1285.2	0.06298	257.74	437.55	1.1952	1.7622	1.366	0.967	1.117
46	0.30403	1279.3	0.05923	260.48	439.01	1.2038	1.7632	1.371	0.974	1.119
48	0.32364	1273.4	0.05575	263.23	440.47	1.2123	1.7642	1.377	0.981	1.121
50	0.34421	1267.5	0.05251	266.00	441.93	1.2209	1.7653	1.383	0.989	1.123
52	0.36576	1261.5	0.04949	268.77	443.38	1.2294	1.7664	1.389	0.996	1.125
54	0.38833	1255.4	0.04667	271.56	444.82	1.2379	1.7675	1.395	1.004	1.128
56	0.41195	1249.3	0.04405	274.36	446.26	1.2463	1.7686	1.401	1.012	1.130
58	0.43665	1243.2	0.04159	277.17	447.69	1.2548	1.7697	1.407	1.021	1.133
60	0.46246	1236.9	0.03930	279.99	449.11	1.2632	1.7709	1.414	1.029	1.135
62	0.48941	1230.6	0.03715	282.83	450.53	1.2717	1.7720	1.420	1.038	1.138
64	0.51754	1224.3	0.03514	285.68	451.94	1.2801	1.7732	1.427	1.046	1.141
66	0.54689	1217.8	0.03326	288.54	453.34	1.2885	1.7744	1.434	1.056	1.145
68	0.57747	1211.3	0.03149	291.42	454.73	1.2968	1.7755	1.441	1.065	1.148
70	0.60933	1204.7	0.02984	294.31	456.11	1.3052	1.7767	1.448	1.075	1.152
72	0.64250	1198.0	0.02828	297.22	457.48	1.3136	1.7779	1.456	1.084	1.156
74	0.67702	1191.3	0.02681	300.13	458.84	1.3219	1.7791	1.464	1.095	1.160
76	0.71292	1184.4	0.02543	303.07	460.19	1.3303	1.7803	1.472	1.105	1.165
78	0.75024	1177.5	0.02414	306.02	461.53	1.3386	1.7815	1.480	1.116	1.169
80	0.78901	1170.5	0.02291	308.98	462.86	1.3469	1.7826	1.488	1.128	1.175
82	0.82927	1163.4	0.02176	311.96	464.17	1.3552	1.7838	1.497	1.140	1.180
84	0.87105	1156.1	0.02067	314.96	465.46	1.3636	1.7850	1.506	1.152	1.186
86	0.91440	1148.8	0.01964	317.97	466.74	1.3719	1.7861	1.516	1.165	1.192
88	0.95935	1141.3	0.01867	321.01	468.01	1.3802	1.7872	1.525	1.178	1.199
90	1.0059	1133.7	0.01774	324.06	469.26	1.3885	1.7883	1.536	1.192	1.206
92	1.0542	1126.0	0.01687	327.12	470.48	1.3968	1.7894	1.546	1.207	1.214
94	1.1042	1118.2	0.01605	330.21	471.69	1.4051	1.7905	1.557	1.223	1.222
96	1.1559	1110.2	0.01526	333.32	472.88	1.4134	1.7915	1.569	1.239	1.231
98	1.2095	1102.0	0.01452	336.45	474.04	1.4217	1.7925	1.582	1.257	1.241
100	1.2649	1093.7	0.01381	339.60	475.19	1.4301	1.7934	1.595	1.275	1.252
105	1.4117	1072.1	0.01220	347.57	477.92	1.4509	1.7956	1.630	1.327	1.283
110	1.5711	1049.3	0.01077	355.71	480.46	1.4719	1.7975	1.673	1.389	1.323
115	1.7437	1024.9	0.00950	364.02	482.77	1.4930	1.7990	1.723	1.466	1.374
120	1.9304	998.6	0.00836	372.54	484.79	1.5144	1.7999	1.786	1.563	1.442
125	2.1320	970.0	0.00734	381.31	486.45	1.5360	1.8001	1.867	1.693	1.535
130	2.3495	938.4	0.00641	390.39	487.64	1.5581	1.7993	1.977	1.875	1.670
135	2.5841	902.7	0.00555	399.87	488.22	1.5809	1.7973	2.137	2.148	1.877
140	2.8370	861.1	0.00476	409.90	487.91	1.6046	1.7934	2.398	2.606	2.232
145	3.1099	810.0	0.00399	420.80	486.22	1.6300	1.7865	2.927	3.536	2.961
150	3.4050	738.4	0.00321	433.55	481.69	1.6594	1.7732	4.734	6.570	5.361
153.86[c]	3.6510	519.4	0.00193	459.00	459.00	1.7183	1.7183	∞	∞	∞

[b]Normal boiling point [c]Critical point

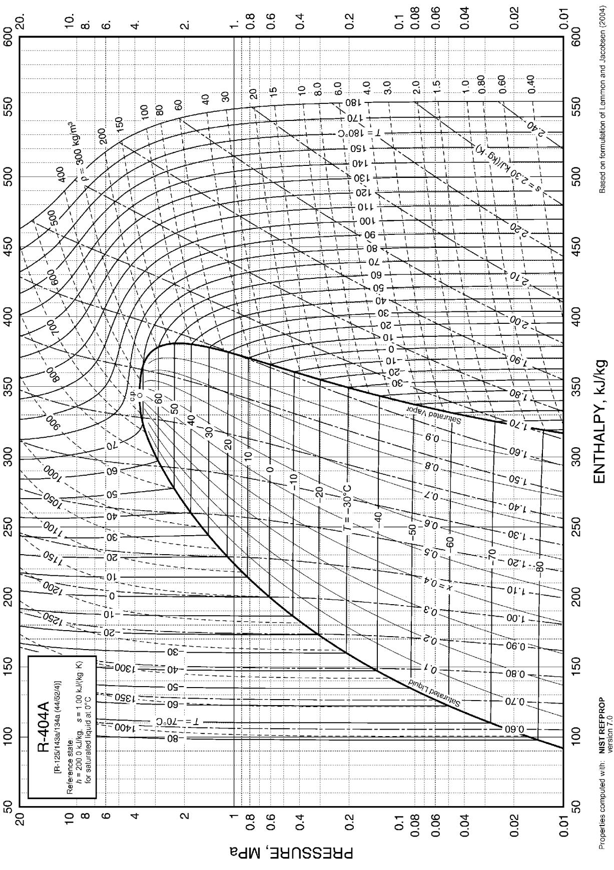


Figure 8.5 Pressure-Enthalpy Diagram for Refrigerant 404A [2017F, Ch 30, Fig 15]

Table 8.8 R-404A [R-125/143a/134a (44/52/4)]
Properties of Liquid on Bubble Line and Vapor on Dew Line [2017F, Ch 30, Tbl R-404A]

Pressure, MPa	Temperature,* °C		Density, kg/m³	Volume, m³/kg	Enthalpy, kJ/kg		Entropy, kJ/(kg·K)		Specific Heat c_p, kJ/(kg·K)		c_p/c_v
	Bubble	Dew	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor
0.005	–93.70	–92.50	1447.1	3.05794	81.16	311.61	0.4716	1.7532	1.220	0.640	1.163
0.006	–91.48	–90.32	1440.6	2.57690	83.85	312.92	0.4865	1.7450	1.218	0.646	1.162
0.007	–89.56	–88.42	1434.9	2.22992	86.19	314.06	0.4993	1.7382	1.216	0.651	1.161
0.008	–87.86	–86.74	1429.9	1.96748	88.26	315.07	0.5106	1.7324	1.215	0.655	1.161
0.009	–86.32	–85.22	1425.4	1.76182	90.13	315.99	0.5206	1.7273	1.214	0.660	1.160
0.01	–84.93	–83.84	1421.3	1.59620	91.83	316.83	0.5296	1.7229	1.214	0.663	1.160
0.02	–75.05	–74.08	1392.4	0.83425	103.81	322.78	0.5917	1.6953	1.215	0.691	1.159
0.04	–63.85	–62.97	1359.4	0.43619	117.48	329.58	0.6587	1.6707	1.225	0.725	1.159
0.06	–56.57	–55.75	1337.7	0.29837	126.44	334.00	0.7007	1.6578	1.234	0.749	1.161
0.08	–51.03	–50.25	1321.0	0.22779	133.31	337.36	0.7320	1.6494	1.243	0.767	1.163
0.1	–46.50	–45.74	1307.1	0.18467	138.97	340.08	0.7571	1.6434	1.251	0.784	1.166
0.10132[b]	–46.22	–45.47	1306.3	0.18240	139.31	340.25	0.7586	1.6430	1.252	0.785	1.166
0.12	–42.63	–41.90	1295.1	0.15551	143.83	342.40	0.7783	1.6387	1.259	0.798	1.169
0.14	–39.24	–38.53	1284.5	0.13443	148.12	344.41	0.7967	1.6349	1.266	0.811	1.171
0.16	–36.20	–35.51	1275.0	0.11846	151.97	346.20	0.8130	1.6318	1.273	0.823	1.174
0.18	–33.45	–32.78	1266.2	0.10592	155.49	347.81	0.8277	1.6292	1.279	0.834	1.177
0.2	–30.93	–30.27	1258.0	0.09581	158.73	349.28	0.8411	1.6270	1.285	0.844	1.179
0.22	–28.59	–27.94	1250.4	0.08748	161.75	350.63	0.8534	1.6250	1.291	0.855	1.182
0.24	–26.42	–25.78	1243.3	0.08049	164.57	351.88	0.8649	1.6233	1.297	0.864	1.185
0.26	–24.37	–23.75	1236.5	0.07454	167.23	353.04	0.8755	1.6217	1.303	0.873	1.188
0.28	–22.45	–21.83	1230.1	0.06941	169.75	354.13	0.8855	1.6203	1.308	0.882	1.190
0.3	–20.62	–20.02	1223.9	0.06494	172.14	355.15	0.8950	1.6190	1.313	0.891	1.193
0.32	–18.89	–18.29	1218.0	0.06101	174.43	356.12	0.9039	1.6179	1.319	0.899	1.196
0.34	–17.24	–16.65	1212.4	0.05752	176.61	357.03	0.9125	1.6168	1.324	0.907	1.199
0.36	–15.66	–15.08	1206.9	0.05441	178.71	357.90	0.9206	1.6158	1.329	0.915	1.202
0.38	–14.15	–13.57	1201.6	0.05162	180.73	358.72	0.9283	1.6149	1.334	0.923	1.205
0.4	–12.69	–12.12	1196.5	0.04909	182.68	359.51	0.9358	1.6141	1.339	0.931	1.208
0.42	–11.29	–10.73	1191.6	0.04680	184.56	360.26	0.9429	1.6133	1.344	0.938	1.211
0.44	–9.94	–9.39	1186.7	0.04471	186.38	360.98	0.9498	1.6125	1.349	0.946	1.214
0.46	–8.64	–8.09	1182.0	0.04279	188.15	361.67	0.9564	1.6118	1.353	0.953	1.217
0.48	–7.37	–6.83	1177.5	0.04103	189.86	362.33	0.9628	1.6112	1.358	0.960	1.220
0.5	–6.15	–5.61	1173.0	0.03940	191.53	362.96	0.9690	1.6105	1.363	0.967	1.223
0.55	–3.24	–2.72	1162.3	0.03584	195.51	364.45	0.9837	1.6091	1.374	0.984	1.231
0.6	–0.53	–0.02	1152.0	0.03284	199.26	365.81	0.9973	1.6078	1.386	1.001	1.239
0.65	2.02	2.52	1142.3	0.03029	202.81	367.06	1.0101	1.6066	1.397	1.018	1.247
0.7	4.42	4.91	1132.9	0.02809	206.18	368.21	1.0222	1.6055	1.409	1.034	1.256
0.75	6.70	7.18	1123.8	0.02618	209.41	369.28	1.0336	1.6044	1.420	1.051	1.264
0.8	8.87	9.34	1115.1	0.02449	212.49	370.27	1.0444	1.6035	1.432	1.067	1.274
0.85	10.94	11.40	1106.5	0.02300	215.46	371.19	1.0547	1.6025	1.443	1.084	1.283
0.9	12.92	13.37	1098.2	0.02166	218.32	372.05	1.0646	1.6016	1.455	1.100	1.293
0.95	14.81	15.26	1090.2	0.02046	221.09	372.85	1.0741	1.6007	1.466	1.117	1.303
1.0	16.64	17.08	1082.2	0.01937	223.77	373.59	1.0832	1.5999	1.478	1.134	1.313
1.1	20.09	20.52	1066.9	0.01749	228.89	374.94	1.1005	1.5982	1.503	1.169	1.336
1.2	23.32	23.73	1052.0	0.01590	233.75	376.12	1.1166	1.5965	1.528	1.206	1.360
1.3	26.35	26.75	1037.5	0.01455	238.37	377.14	1.1318	1.5949	1.554	1.244	1.386
1.4	29.22	29.60	1023.4	0.01338	242.81	378.02	1.1462	1.5932	1.582	1.285	1.414
1.5	31.93	32.30	1009.5	0.01236	247.07	378.78	1.1599	1.5914	1.611	1.329	1.445
1.6	34.51	34.87	995.7	0.01146	251.19	379.42	1.1730	1.5896	1.643	1.376	1.478
1.7	36.97	37.32	982.1	0.01066	255.17	379.95	1.1856	1.5878	1.676	1.426	1.515
1.8	39.33	39.67	968.6	0.00994	259.05	380.38	1.1977	1.5858	1.712	1.481	1.556
1.9	41.58	41.91	955.1	0.00930	262.83	380.70	1.2095	1.5838	1.751	1.541	1.601
2.0	43.75	44.07	941.6	0.00871	266.52	380.92	1.2208	1.5817	1.794	1.607	1.652
2.1	45.84	46.15	928.1	0.00817	270.14	381.05	1.2319	1.5794	1.841	1.681	1.709
2.2	47.85	48.15	914.4	0.00768	273.70	381.08	1.2427	1.5770	1.893	1.763	1.774
2.3	49.80	50.08	900.6	0.00723	277.20	381.01	1.2532	1.5745	1.952	1.856	1.847
2.4	51.68	51.95	886.5	0.00680	280.66	380.83	1.2635	1.5718	2.019	1.962	1.932
2.5	53.50	53.76	872.2	0.00641	284.09	380.55	1.2737	1.5689	2.095	2.085	2.032
2.6	55.26	55.51	857.5	0.00604	287.50	380.15	1.2837	1.5658	2.183	2.229	2.149
2.7	56.97	57.21	842.4	0.00569	290.89	379.62	1.2937	1.5624	2.288	2.401	2.289
2.8	58.63	58.86	826.8	0.00536	294.29	378.96	1.3036	1.5587	2.414	2.609	2.459
2.9	60.24	60.46	810.5	0.00505	297.70	378.14	1.3135	1.5547	2.569	2.868	2.672
3.0	61.81	62.01	793.4	0.00475	301.15	377.15	1.3234	1.5503	2.765	3.197	2.944
3.2	64.82	64.99	755.6	0.00417	308.25	374.49	1.3438	1.5397	3.381	4.233	3.797
3.4	67.67	67.81	709.8	0.00361	315.97	370.45	1.3657	1.5255	4.771	6.536	5.689
3.729[c]	72.05	72.05	486.5	0.00206	343.92	343.92	1.4455	1.4455	—	—	—

*Temperatures on ITS-90 scale

[b]Bubble and dew points at one standard atmosphere

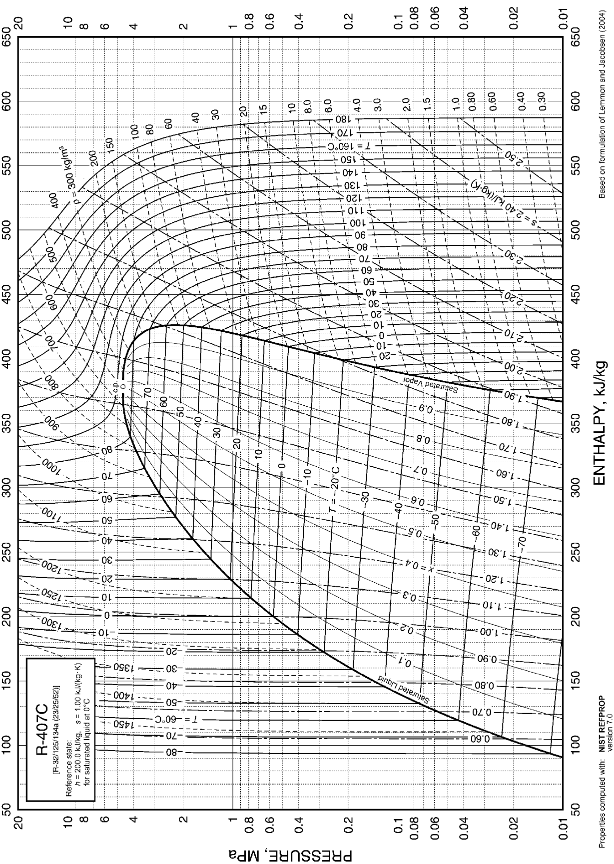


Figure 8.6 Pressure-Enthalpy Diagram for Refrigerant 407C [2017F, Ch 30, Fig 16]

Table 8.9 R-407C [R-32/125/134a (23/25/52)] Properties of Liquid on Bubble Line and Vapor on Dew Line [2017F, Ch 30, Tbl R-407C]

Pressure, MPa	Temperature,* °C		Density, kg/m³	Volume, m³/kg	Enthalpy, kJ/kg		Entropy, kJ/(kg·K)		Specific Heat c_p, kJ/(kg·K)		c_p/c_v
	Bubble	Dew	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor
0.01	–82.45	–74.81	1495.5	1.89703	90.48	366.78	0.5259	1.9471	1.281	0.668	1.182
0.02	–72.50	–65.02	1466.7	0.99017	103.24	372.75	0.5910	1.9104	1.283	0.694	1.181
0.04	–61.25	–53.95	1433.7	0.51705	117.72	379.47	0.6612	1.8761	1.291	0.727	1.182
0.06	–53.96	–46.79	1412.0	0.35346	127.17	383.77	0.7050	1.8573	1.299	0.750	1.184
0.08	–48.42	–41.34	1395.3	0.26975	134.39	386.99	0.7374	1.8445	1.306	0.769	1.187
0.1	–43.90	–36.90	1381.5	0.21865	140.31	389.59	0.7635	1.8349	1.312	0.786	1.190
0.10132[b]	–43.63	–36.63	1380.7	0.21595	140.67	389.75	0.7650	1.8343	1.312	0.787	1.190
0.12	–40.05	–33.11	1369.7	0.18411	145.39	391.78	0.7854	1.8273	1.318	0.800	1.193
0.14	–36.67	–29.79	1359.1	0.15916	149.86	393.68	0.8043	1.8210	1.324	0.813	1.196
0.16	–33.65	–26.83	1349.7	0.14025	153.86	395.36	0.8211	1.8156	1.329	0.825	1.199
0.18	–30.92	–24.15	1341.0	0.12542	157.51	396.86	0.8362	1.8110	1.334	0.837	1.201
0.2	–28.41	–21.69	1333.0	0.11347	160.87	398.22	0.8499	1.8069	1.339	0.848	1.204
0.22	–26.09	–19.41	1325.5	0.10362	163.99	399.47	0.8625	1.8033	1.344	0.858	1.207
0.24	–23.93	–17.29	1318.4	0.09536	166.91	400.62	0.8742	1.8000	1.349	0.868	1.210
0.26	–21.90	–15.31	1311.8	0.08833	169.65	401.69	0.8851	1.7970	1.354	0.877	1.213
0.28	–19.99	–13.43	1305.5	0.08227	172.24	402.69	0.8954	1.7942	1.358	0.886	1.216
0.3	–18.19	–11.66	1299.5	0.07699	174.71	403.62	0.9050	1.7917	1.362	0.895	1.219
0.32	–16.47	–9.98	1293.7	0.07235	177.06	404.49	0.9141	1.7894	1.367	0.903	1.222
0.34	–14.83	–8.38	1288.2	0.06824	179.30	405.32	0.9228	1.7872	1.371	0.911	1.224
0.36	–13.27	–6.85	1282.9	0.06457	181.45	406.10	0.9310	1.7851	1.375	0.919	1.227
0.38	–11.77	–5.38	1277.8	0.06127	183.52	406.85	0.9389	1.7832	1.379	0.927	1.230
0.4	–10.33	–3.97	1272.8	0.05830	185.52	407.55	0.9465	1.7814	1.383	0.934	1.233
0.42	–8.94	–2.61	1268.0	0.05559	187.44	408.23	0.9537	1.7796	1.387	0.942	1.236
0.44	–7.61	–1.31	1263.4	0.05313	189.30	408.87	0.9607	1.7780	1.391	0.949	1.239
0.46	–6.31	–0.04	1258.8	0.05087	191.11	409.48	0.9674	1.7764	1.395	0.956	1.242
0.48	–5.06	1.18	1254.4	0.04879	192.86	410.07	0.9739	1.7750	1.399	0.963	1.245
0.5	–3.85	2.36	1250.1	0.04687	194.56	410.64	0.9801	1.7735	1.403	0.970	1.248
0.55	–0.98	5.17	1239.8	0.04267	198.61	411.95	0.9950	1.7702	1.413	0.987	1.255
0.6	1.70	7.79	1230.0	0.03915	202.42	413.15	1.0087	1.7672	1.422	1.004	1.262
0.65	4.22	10.24	1220.7	0.03615	206.02	414.25	1.0216	1.7644	1.432	1.020	1.270
0.7	6.60	12.56	1211.7	0.03356	209.44	415.25	1.0338	1.7618	1.441	1.036	1.278
0.75	8.85	14.76	1203.1	0.03131	212.71	416.18	1.0452	1.7594	1.451	1.052	1.286
0.8	11.00	16.85	1194.9	0.02933	215.83	417.03	1.0561	1.7571	1.460	1.067	1.294
0.85	13.04	18.84	1186.8	0.02757	218.83	417.83	1.0665	1.7550	1.469	1.082	1.302
0.9	15.00	20.74	1179.1	0.02600	221.71	418.57	1.0764	1.7529	1.479	1.098	1.310
0.95	16.88	22.56	1171.5	0.02460	224.50	419.25	1.0859	1.7509	1.488	1.113	1.319
1.0	18.69	24.32	1164.1	0.02332	227.19	419.89	1.0950	1.7491	1.498	1.128	1.327
1.1	22.11	27.63	1149.9	0.02111	232.34	421.03	1.1122	1.7455	1.517	1.159	1.346
1.2	25.30	30.73	1136.2	0.01926	237.20	422.03	1.1283	1.7421	1.537	1.190	1.365
1.3	28.30	33.63	1123.0	0.01768	241.82	422.89	1.1434	1.7389	1.557	1.222	1.385
1.4	31.14	36.37	1110.2	0.01631	246.24	423.63	1.1577	1.7358	1.578	1.255	1.406
1.5	33.83	38.97	1097.7	0.01512	250.48	424.27	1.1713	1.7328	1.600	1.289	1.428
1.6	36.39	41.43	1085.5	0.01408	254.57	424.80	1.1843	1.7298	1.622	1.324	1.452
1.7	38.84	43.78	1073.5	0.01315	258.51	425.25	1.1967	1.7269	1.645	1.361	1.477
1.8	41.18	46.03	1061.7	0.01231	262.33	425.61	1.2086	1.7241	1.669	1.400	1.504
1.9	43.43	48.18	1050.0	0.01157	266.05	425.89	1.2200	1.7212	1.695	1.440	1.533
2.0	45.59	50.25	1038.5	0.01089	269.66	426.10	1.2311	1.7184	1.722	1.483	1.564
2.1	47.67	52.24	1027.1	0.01027	273.19	426.23	1.2418	1.7155	1.750	1.529	1.597
2.2	49.68	54.15	1015.7	0.00971	276.64	426.29	1.2522	1.7126	1.780	1.577	1.633
2.3	51.63	56.00	1004.4	0.00919	280.02	426.28	1.2624	1.7097	1.813	1.629	1.671
2.4	53.51	57.79	993.1	0.00871	283.34	426.20	1.2723	1.7068	1.847	1.684	1.713
2.5	55.34	59.51	981.8	0.00827	286.60	426.06	1.2819	1.7038	1.884	1.744	1.758
2.6	57.11	61.19	970.5	0.00786	289.82	425.85	1.2914	1.7007	1.924	1.810	1.808
2.7	58.83	62.81	959.0	0.00747	292.99	425.57	1.3006	1.6976	1.968	1.881	1.863
2.8	60.51	64.38	947.5	0.00711	296.12	425.21	1.3097	1.6944	2.016	1.958	1.923
2.9	62.14	65.91	935.9	0.00677	299.23	424.79	1.3187	1.6911	2.069	2.044	1.990
3.0	63.73	67.40	924.1	0.00645	302.31	424.29	1.3276	1.6877	2.128	2.139	2.065
3.2	66.80	70.25	899.9	0.00587	308.43	423.06	1.3450	1.6805	2.268	2.365	2.243
3.4	69.73	72.94	874.6	0.00533	314.54	421.46	1.3622	1.6726	2.451	2.657	2.475
3.6	72.53	75.50	847.6	0.00484	320.71	419.45	1.3795	1.6639	2.701	3.050	2.789
3.8	75.22	77.92	818.1	0.00439	327.02	416.91	1.3970	1.6540	3.065	3.613	3.239
4.0	77.82	80.21	785.1	0.00395	333.64	413.66	1.4152	1.6424	3.647	4.486	3.935
4.2	80.32	82.37	746.0	0.00352	340.83	409.34	1.4348	1.6281	4.726	6.029	5.159
4.63[c]	86.03	86.03	484.2	0.00207	378.48	378.48	1.5384	1.5384	—	—	—

*Temperatures on ITS-90 scale [b]Bubble and dew points at one standard atmosphere [c]Critical point

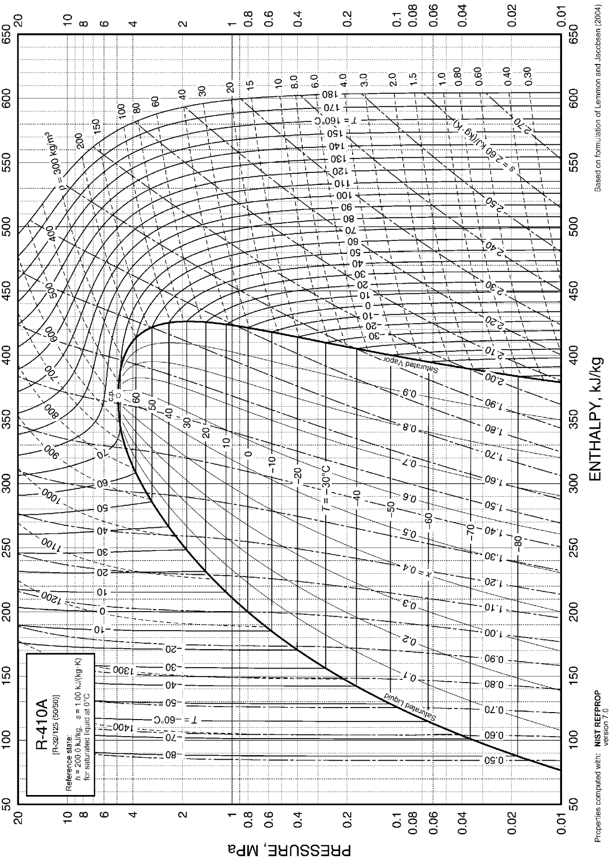


Figure 8.7 Pressure-Enthalpy Diagram for Refrigerant 410A [2017F, Ch 30, Fig 17]

Table 8.10 R-410A [R-32/125 (50/50)] Properties of Liquid on Bubble Line and Vapor on Dew Line [2017F, Ch 30, Tbl R-410A]

Pressure, MPa	Temperature,* °C		Density, kg/m³	Volume, m³/kg	Enthalpy, kJ/kg		Entropy, kJ/(kg·K)		Specific Heat c_p, kJ/(kg·K)		c_p/c_v
	Bubble	Dew	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor
0.01	–88.23	–88.14	1460.6	2.09888	76.56	378.76	0.4588	2.0927	1.344	0.668	1.227
0.02	–78.79	–78.70	1432.9	1.09659	89.26	384.25	0.5258	2.0432	1.345	0.696	1.228
0.04	–68.12	–68.04	1401.1	0.57309	103.64	390.29	0.5978	1.9956	1.351	0.734	1.231
0.06	–61.22	–61.14	1380.0	0.39193	113.00	394.10	0.6426	1.9687	1.358	0.762	1.235
0.08	–55.98	–55.90	1363.9	0.29918	120.14	396.92	0.6758	1.9500	1.364	0.785	1.239
0.1	–51.70	–51.62	1350.5	0.24256	125.99	399.17	0.7024	1.9358	1.369	0.805	1.243
0.10132[b]	–51.44	–51.36	1349.7	0.23957	126.34	399.31	0.7040	1.9350	1.370	0.807	1.244
0.12	–48.06	–47.98	1339.0	0.20427	130.99	401.05	0.7247	1.9243	1.375	0.823	1.247
0.14	–44.87	–44.79	1328.8	0.17661	135.39	402.67	0.7441	1.9147	1.380	0.839	1.251
0.16	–42.02	–41.94	1319.6	0.15565	139.34	404.09	0.7612	1.9065	1.385	0.854	1.255
0.18	–39.44	–39.36	1311.2	0.13921	142.93	405.36	0.7766	1.8993	1.390	0.868	1.259
0.2	–37.07	–36.99	1303.4	0.12595	146.23	406.50	0.7905	1.8928	1.395	0.881	1.263
0.22	–34.89	–34.80	1296.2	0.11503	149.29	407.53	0.8034	1.8871	1.399	0.893	1.266
0.24	–32.85	–32.76	1289.4	0.10587	152.15	408.49	0.8153	1.8818	1.404	0.904	1.270
0.26	–30.94	–30.85	1283.0	0.09807	154.84	409.36	0.8264	1.8770	1.408	0.916	1.274
0.28	–29.14	–29.05	1276.9	0.09135	157.38	410.18	0.8368	1.8726	1.413	0.926	1.277
0.3	–27.44	–27.35	1271.1	0.08550	159.80	410.94	0.8466	1.8685	1.417	0.936	1.281
0.32	–25.82	–25.73	1265.5	0.08035	162.10	411.65	0.8558	1.8647	1.421	0.946	1.285
0.34	–24.28	–24.19	1260.2	0.07579	164.29	412.32	0.8646	1.8611	1.426	0.956	1.288
0.36	–22.81	–22.72	1255.0	0.07172	166.40	412.95	0.8703	1.8577	1.430	0.965	1.292
0.38	–21.40	–21.31	1250.1	0.06806	168.43	413.54	0.8810	1.8545	1.434	0.975	1.295
0.4	–20.04	–19.95	1245.3	0.06476	170.38	414.10	0.8887	1.8514	1.438	0.983	1.299
0.42	–18.74	–18.65	1240.6	0.06176	172.26	414.64	0.8960	1.8486	1.443	0.992	1.303
0.44	–17.48	–17.39	1236.1	0.05902	174.08	415.14	0.9031	1.8458	1.447	1.001	1.306
0.46	–16.27	–16.18	1231.8	0.05652	175.84	415.63	0.9099	1.8432	1.451	1.009	1.310
0.48	–15.10	–15.00	1227.5	0.05421	177.55	416.09	0.9165	1.8407	1.455	1.017	1.313
0.5	–13.96	–13.86	1223.3	0.05209	179.21	416.53	0.9228	1.8383	1.459	1.025	1.317
0.55	–11.26	–11.16	1213.4	0.04743	183.17	417.54	0.9379	1.8326	1.469	1.045	1.326
0.6	–8.74	–8.64	1203.9	0.04352	186.89	418.46	0.9518	1.8275	1.479	1.064	1.335
0.65	–6.38	–6.28	1194.9	0.04019	190.40	419.28	0.9649	1.8227	1.489	1.083	1.344
0.7	–4.15	–4.05	1186.3	0.03732	193.74	420.03	0.9772	1.8183	1.499	1.101	1.354
0.75	–2.04	–1.93	1178.1	0.03482	196.92	420.71	0.9888	1.8141	1.509	1.119	1.363
0.8	–0.03	0.08	1170.1	0.03262	199.96	421.33	0.9998	1.8102	1.519	1.136	1.373
0.85	1.89	1.99	1162.4	0.03068	202.88	421.89	1.0103	1.8065	1.529	1.154	1.382
0.9	3.72	3.83	1154.9	0.02894	205.69	422.41	1.0204	1.8030	1.540	1.171	1.392
0.95	5.48	5.58	1147.6	0.02738	208.40	422.88	1.0300	1.7996	1.550	1.188	1.402
1.0	7.17	7.27	1140.5	0.02596	211.02	423.31	1.0392	1.7964	1.560	1.205	1.413
1.1	10.36	10.47	1126.8	0.02351	216.03	424.07	1.0567	1.7903	1.581	1.239	1.434
1.2	13.34	13.46	1113.7	0.02145	220.76	424.68	1.0730	1.7846	1.603	1.274	1.457
1.3	16.15	16.26	1101.0	0.01970	225.26	425.19	1.0883	1.7792	1.624	1.31	1.481
1.4	18.79	18.91	1088.8	0.01819	229.56	425.59	1.1027	1.7741	1.647	1.347	1.506
1.5	21.30	21.41	1076.9	0.01687	233.68	425.89	1.1165	1.7691	1.670	1.385	1.532
1.6	23.68	23.80	1065.2	0.01571	237.65	426.11	1.1296	1.7644	1.694	1.424	1.560
1.7	25.96	26.07	1053.8	0.01468	241.48	426.25	1.1421	1.7597	1.719	1.465	1.590
1.8	28.13	28.25	1042.6	0.01376	245.19	426.31	1.1542	1.7552	1.745	1.509	1.621
1.9	30.22	30.34	1031.6	0.01293	248.79	426.31	1.1657	1.7508	1.772	1.555	1.655
2.0	32.22	32.34	1020.7	0.01218	252.29	426.24	1.1769	1.7464	1.800	1.603	1.690
2.1	34.16	34.28	1009.9	0.0115	255.71	426.10	1.1878	1.7421	1.830	1.655	1.728
2.2	36.02	36.14	999.2	0.01088	259.05	425.90	1.1983	1.7379	1.861	1.709	1.769
2.3	37.82	37.94	988.6	0.01031	262.32	425.64	1.2085	1.7336	1.894	1.768	1.813
2.4	39.56	39.68	978.0	0.00978	265.52	425.33	1.2185	1.7294	1.929	1.831	1.860
2.5	41.25	41.37	967.5	0.00929	268.67	424.95	1.2282	1.7251	1.967	1.898	1.911
2.6	42.89	43.00	957.0	0.00883	271.77	424.51	1.2377	1.7209	2.008	1.971	1.966
2.7	44.48	44.59	946.4	0.00841	274.82	424.02	1.2470	1.7166	2.052	2.050	2.026
2.8	46.02	46.14	935.8	0.00802	277.84	423.47	1.2561	1.7123	2.100	2.136	2.091
2.9	47.53	47.64	925.2	0.00764	280.82	422.85	1.2651	1.7079	2.153	2.230	2.163
3.0	48.99	49.10	914.5	0.00729	283.78	422.18	1.2740	1.7035	2.211	2.333	2.243
3.2	51.81	51.91	892.6	0.00665	289.62	420.62	1.2913	1.6944	2.348	2.575	2.429
3.4	54.49	54.59	870.0	0.00607	295.43	418.78	1.3085	1.6849	2.522	2.879	2.663
3.6	57.05	57.15	846.3	0.00555	301.26	416.60	1.3254	1.6747	2.752	3.276	2.970
3.8	59.50	59.59	821.0	0.00506	307.16	414.03	1.3425	1.6638	3.070	3.815	3.386
4.0	61.85	61.93	793.5	0.00460	313.24	410.97	1.3600	1.6517	3.541	4.596	3.987
4.2	64.10	64.17	762.6	0.00417	319.65	407.24	1.3783	1.6380	4.306	5.826	4.929
4.903[c]	71.36	71.36	459.5	0.00218	368.55	368.55	1.5181	1.5181	—	—	—

*Temperatures on ITS-90 scale [b]Bubble and dew points at one standard atmosphere [c]Critical point

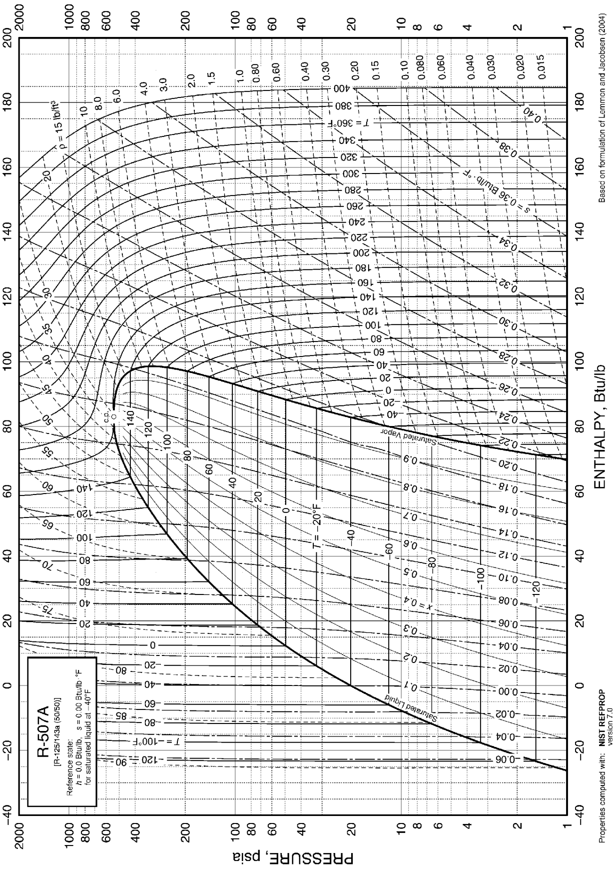


Figure 8.8 Pressure-Enthalpy Diagram for Refrigerant 507A [2017F, Ch 30, Fig 18]

Table 8.11 R-507A [R-125/143a (50/50)] Properties of Saturated Liquid and Saturated Vapor [2017F, Ch 30, Tbl R-507A]

Temp.,* °C	Pressure,** MPa	Density, kg/m³ Liquid	Volume, m³/kg Vapor	Enthalpy, kJ/kg Liquid	Enthalpy, kJ/kg Vapor	Entropy, kJ/(kg·K) Liquid	Entropy, kJ/(kg·K) Vapor	Specific Heat c_p, kJ/(kg·K) Liquid	Specific Heat c_p, kJ/(kg·K) Vapor	c_p/c_v Vapor
–100	0.00295	1476.9	4.92920	74.41	303.90	0.4323	1.7579	1.219	0.618	1.164
–95	0.00458	1461.7	3.25360	80.48	306.85	0.4669	1.7377	1.210	0.631	1.162
–90	0.00693	1446.8	2.20850	86.51	309.83	0.5003	1.7197	1.205	0.644	1.161
–85	0.01019	1431.9	1.53750	92.53	312.83	0.5327	1.7036	1.203	0.658	1.159
–80	0.01464	1417.1	1.09510	98.54	315.85	0.5642	1.6893	1.203	0.672	1.159
–75	0.02058	1402.3	0.79638	104.57	318.88	0.5950	1.6766	1.205	0.686	1.158
–70	0.02836	1387.4	0.59012	110.60	321.92	0.6250	1.6652	1.208	0.701	1.158
–65	0.03837	1372.5	0.44482	116.66	324.96	0.6545	1.6552	1.213	0.716	1.159
–60	0.05105	1357.4	0.34056	122.74	328.00	0.6833	1.6463	1.220	0.732	1.160
–55	0.06688	1342.3	0.26444	128.87	331.03	0.7116	1.6384	1.227	0.749	1.161
–50	0.08638	1326.9	0.20801	135.03	334.05	0.7395	1.6314	1.235	0.766	1.164
–48	0.09533	1320.7	0.18960	137.51	335.25	0.7505	1.6288	1.239	0.773	1.165
–46.74[b]	0.10132	1316.8	0.17902	139.07	336.01	0.7574	1.6273	1.241	0.777	1.166
–46	0.10499	1314.5	0.17313	139.99	336.45	0.7615	1.6264	1.243	0.780	1.166
–44	0.11541	1308.2	0.15836	142.48	337.65	0.7724	1.6241	1.247	0.787	1.167
–42	0.12662	1301.9	0.14510	144.99	338.84	0.7832	1.6219	1.251	0.795	1.169
–40	0.13867	1295.6	0.13317	147.49	340.03	0.7940	1.6198	1.255	0.803	1.170
–38	0.15159	1289.2	0.12240	150.01	341.21	0.8047	1.6178	1.259	0.810	1.172
–36	0.16542	1282.8	0.11268	152.54	342.38	0.8153	1.6159	1.264	0.818	1.174
–34	0.18022	1276.3	0.10388	155.08	343.55	0.8260	1.6141	1.269	0.826	1.176
–32	0.19602	1269.7	0.09590	157.63	344.72	0.8365	1.6123	1.274	0.835	1.178
–30	0.21287	1263.2	0.08865	160.18	345.88	0.8470	1.6107	1.279	0.843	1.180
–28	0.23081	1256.5	0.08205	162.75	347.03	0.8575	1.6092	1.284	0.852	1.183
–26	0.24989	1249.8	0.07604	165.33	348.17	0.8679	1.6077	1.289	0.861	1.186
–24	0.27016	1243.1	0.07055	167.92	349.30	0.8783	1.6063	1.295	0.870	1.188
–22	0.29167	1236.3	0.06553	170.52	350.43	0.8886	1.6049	1.301	0.879	1.191
–20	0.31446	1229.4	0.06094	173.13	351.54	0.8989	1.6037	1.307	0.888	1.195
–18	0.33858	1222.5	0.05673	175.76	352.65	0.9091	1.6024	1.313	0.898	1.198
–16	0.36408	1215.4	0.05286	178.39	353.75	0.9193	1.6013	1.319	0.908	1.202
–14	0.39102	1208.4	0.04931	181.04	354.83	0.9295	1.6001	1.326	0.918	1.206
–12	0.41945	1201.2	0.04603	183.71	355.91	0.9397	1.5991	1.333	0.929	1.210
–10	0.44941	1193.9	0.04301	186.39	356.97	0.9498	1.5980	1.340	0.940	1.214
–8	0.48096	1186.6	0.04023	189.08	358.02	0.9599	1.5971	1.348	0.951	1.219
–6	0.51416	1179.2	0.03765	191.78	359.06	0.9699	1.5961	1.355	0.962	1.224
–4	0.54906	1171.7	0.03527	194.51	360.08	0.9800	1.5952	1.363	0.974	1.230
–2	0.58571	1164.0	0.03306	197.25	361.08	0.9900	1.5943	1.372	0.987	1.236
0	0.62417	1156.3	0.03101	200.00	362.07	1.0000	1.5934	1.381	0.999	1.242
2	0.66450	1148.5	0.02910	202.77	363.05	1.0100	1.5925	1.390	1.012	1.249
4	0.70676	1140.5	0.02733	205.56	364.00	1.0199	1.5917	1.399	1.026	1.256
6	0.75099	1132.4	0.02568	208.37	364.94	1.0299	1.5908	1.410	1.040	1.264
8	0.79728	1124.2	0.02415	211.20	365.85	1.0398	1.5900	1.420	1.055	1.272
10	0.84566	1115.9	0.02271	214.04	366.75	1.0498	1.5891	1.431	1.071	1.282
12	0.89622	1107.4	0.02138	216.91	367.61	1.0597	1.5883	1.443	1.088	1.291
14	0.94900	1098.7	0.02012	219.80	368.46	1.0696	1.5874	1.455	1.105	1.302
16	1.00410	1089.9	0.01895	222.71	369.28	1.0796	1.5865	1.468	1.124	1.314
18	1.06150	1080.9	0.01785	225.65	370.07	1.0895	1.5856	1.482	1.144	1.327
20	1.12140	1071.7	0.01683	228.61	370.83	1.0995	1.5846	1.497	1.165	1.341
22	1.18370	1062.4	0.01586	231.60	371.55	1.1094	1.5836	1.513	1.188	1.356
24	1.24860	1052.8	0.01495	234.61	372.25	1.1194	1.5826	1.530	1.212	1.372
26	1.31610	1043.0	0.01410	237.66	372.91	1.1294	1.5815	1.548	1.239	1.391
28	1.38640	1032.9	0.01329	240.73	373.52	1.1394	1.5804	1.568	1.268	1.411
30	1.45940	1022.6	0.01253	243.84	374.10	1.1495	1.5792	1.589	1.299	1.433
32	1.53520	1011.9	0.01182	246.98	374.63	1.1595	1.5779	1.612	1.333	1.458
34	1.61400	1001.0	0.01114	250.16	375.11	1.1697	1.5765	1.637	1.371	1.485
36	1.69580	989.7	0.01050	253.39	375.54	1.1799	1.5750	1.664	1.413	1.516
38	1.78070	978.1	0.00989	256.65	375.91	1.1901	1.5734	1.695	1.459	1.551
40	1.86880	966.0	0.00932	259.96	376.22	1.2004	1.5717	1.729	1.511	1.591
42	1.96020	953.5	0.00877	263.33	376.46	1.2108	1.5698	1.767	1.570	1.636
44	2.05490	940.5	0.00825	266.74	376.61	1.2213	1.5678	1.811	1.638	1.689
46	2.15310	926.9	0.00776	270.23	376.68	1.2320	1.5655	1.860	1.716	1.750
48	2.25480	912.7	0.00728	273.78	376.66	1.2427	1.5631	1.918	1.807	1.823
50	2.36030	897.7	0.00683	277.41	376.52	1.2536	1.5603	1.985	1.915	1.910
55	2.64090	856.2	0.00578	286.91	375.54	1.2818	1.5519	2.225	2.304	2.228
60	2.94760	806.1	0.00480	297.28	373.26	1.3120	1.5401	2.677	3.060	2.855
65	3.28380	739.1	0.00384	309.30	368.44	1.3465	1.5215	3.940	5.190	4.625
70	3.65570	599.6	0.00260	328.32	353.47	1.4007	1.4740	31.960	44.630	36.780
70.62[c]	3.70500	490.8	0.00204	340.45	340.45	1.4358	1.4358	∞	∞	∞

*Temperatures on ITS-90 scale

**Small deviations from azeotropic behavior occur at some conditions; tabulated pressures are average of bubble and dew-point pressures

[b]Normal boiling point

[c]Critical point

Refrigerants

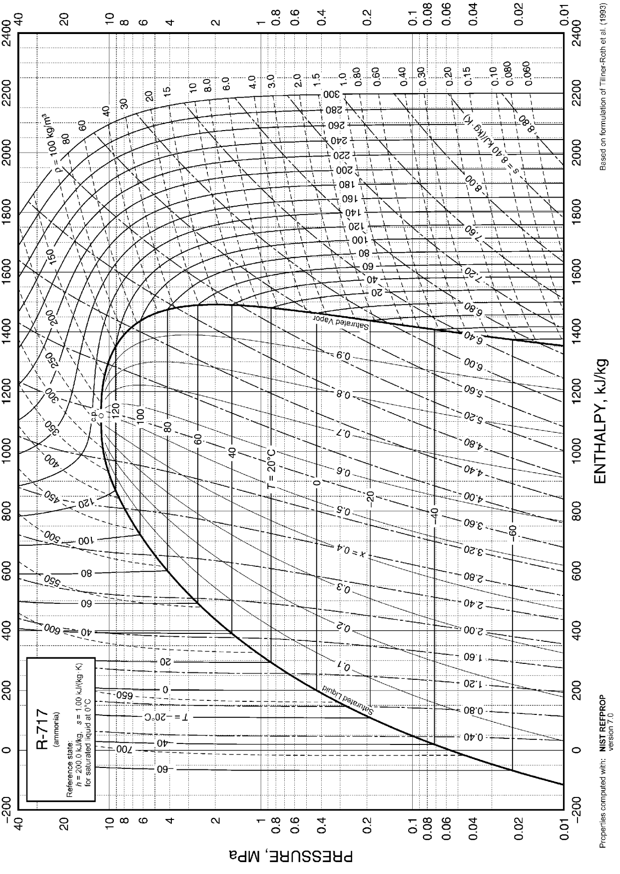


Figure 8.9 Pressure-Enthalpy Diagram for Refrigerant 717 (Ammonia) [2017F, Ch 30, Fig 18]

Table 8.12 R-717 (Ammonia) Properties of Saturated Liquid and Saturated Vapor

[2017F, Ch 30, Tbl R-717]

Temp.,* °C	Pressure, MPa	Density, kg/m³ Liquid	Volume, m³/kg Vapor	Enthalpy, kJ/kg Liquid	Enthalpy, kJ/kg Vapor	Entropy, kJ/(kg·K) Liquid	Entropy, kJ/(kg·K) Vapor	c_p/c_v Vapor
–77.65[a]	0.00609	732.9	15.602	–143.15	1341.23	–0.4716	7.1213	1.325
–70	0.01094	724.7	9.0079	–110.81	1355.55	–0.3094	6.9088	1.327
–60	0.02189	713.6	4.7057	–68.06	1373.73	–0.1040	6.6602	1.330
–50	0.04084	702.1	2.6277	–24.73	1391.19	0.0945	6.4396	1.335
–40	0.07169	690.2	1.5533	19.17	1407.76	0.2867	6.2425	1.342
–38	0.07971	687.7	1.4068	28.01	1410.96	0.3245	6.2056	1.343
–36	0.08845	685.3	1.2765	36.88	1414.11	0.3619	6.1694	1.345
–34	0.09795	682.8	1.1604	45.77	1417.23	0.3992	6.1339	1.347
–33.33[b]	0.10133	682.0	1.1242	48.76	1418.26	0.4117	6.1221	1.348
–32	0.10826	680.3	1.0567	54.67	1420.29	0.4362	6.0992	1.349
–30	0.11943	677.8	0.96396	63.60	1423.31	0.4730	6.0651	1.351
–28	0.13151	675.3	0.88082	72.55	1426.28	0.5096	6.0317	1.353
–26	0.14457	672.8	0.80614	81.52	1429.21	0.5460	5.9989	1.355
–24	0.15864	670.3	0.73896	90.51	1432.08	0.5821	5.9667	1.358
–22	0.17379	667.7	0.67840	99.52	1434.91	0.6180	5.9351	1.360
–20	0.19008	665.1	0.62373	108.55	1437.68	0.6538	5.9041	1.363
–18	0.20756	662.6	0.57428	117.60	1440.39	0.6893	5.8736	1.365
–16	0.22630	660.0	0.52949	126.67	1443.06	0.7246	5.8437	1.368
–14	0.24637	657.3	0.48885	135.76	1445.66	0.7597	5.8143	1.371
–12	0.26782	654.7	0.45192	144.88	1448.21	0.7946	5.7853	1.375
–10	0.29071	652.1	0.41830	154.01	1450.70	0.8293	5.7569	1.378
–8	0.31513	649.4	0.38767	163.16	1453.14	0.8638	5.7289	1.382
–6	0.34114	646.7	0.35970	172.34	1455.51	0.8981	5.7013	1.385
–4	0.36880	644.0	0.33414	181.54	1457.81	0.9323	5.6741	1.389
–2	0.39819	641.3	0.31074	190.76	1460.06	0.9662	5.6474	1.393
0	0.42938	638.6	0.28930	200.00	1462.24	1.0000	5.6210	1.398
2	0.46246	635.8	0.26962	209.27	1464.35	1.0336	5.5951	1.402
4	0.49748	633.1	0.25153	218.55	1466.40	1.0670	5.5695	1.407
6	0.53453	630.3	0.23489	227.87	1468.37	1.1003	5.5442	1.412
8	0.57370	627.5	0.21956	237.20	1470.28	1.1334	5.5192	1.417
10	0.61505	624.6	0.20543	246.57	1472.11	1.1664	5.4946	1.422
12	0.65866	621.8	0.19237	255.95	1473.88	1.1992	5.4703	1.428
14	0.70463	618.9	0.18031	265.37	1475.56	1.2318	5.4463	1.434
16	0.75303	616.0	0.16914	274.81	1477.17	1.2643	5.4226	1.440
18	0.80395	613.1	0.15879	284.28	1478.70	1.2967	5.3991	1.446
20	0.85748	610.2	0.14920	293.78	1480.16	1.3289	5.3759	1.453
22	0.91369	607.2	0.14029	303.31	1481.53	1.3610	5.3529	1.460
24	0.97268	604.3	0.13201	312.87	1482.82	1.3929	5.3301	1.468
26	1.03450	601.3	0.12431	322.47	1484.02	1.4248	5.3076	1.475
28	1.09930	598.2	0.11714	332.09	1485.14	1.4565	5.2853	1.484
30	1.16720	595.2	0.11046	341.76	1486.17	1.4881	5.2631	1.492
32	1.23820	592.1	0.10422	351.45	1487.11	1.5196	5.2412	1.501
34	1.31240	589.0	0.09840	361.19	1487.95	1.5509	5.2194	1.510
36	1.39000	585.8	0.09296	370.96	1488.70	1.5822	5.1978	1.520
38	1.47090	582.6	0.08787	380.78	1489.36	1.6134	5.1763	1.530
40	1.55540	579.4	0.08310	390.64	1489.91	1.6446	5.1549	1.541
42	1.64350	576.2	0.07863	400.54	1490.36	1.6756	5.1337	1.553
44	1.73530	572.9	0.07445	410.48	1490.70	1.7065	5.1126	1.565
46	1.83100	569.6	0.07052	420.48	1490.94	1.7374	5.0915	1.577
48	1.93050	566.3	0.06682	430.52	1491.06	1.7683	5.0706	1.591
50	2.03400	562.9	0.06335	440.62	1491.07	1.7990	5.0497	1.605
55	2.31110	554.2	0.05554	466.10	1490.57	1.8758	4.9977	1.643
60	2.61560	545.2	0.04880	491.97	1489.27	1.9523	4.9458	1.687
65	2.94910	536.0	0.04296	518.26	1487.09	2.0288	4.8939	1.739
70	3.31350	526.3	0.03787	545.04	1483.94	2.1054	4.8415	1.799
75	3.71050	516.2	0.03342	572.37	1479.72	2.1823	4.7885	1.870
80	4.14200	505.7	0.02951	600.34	1474.31	2.2596	4.7344	1.955
85	4.61000	494.5	0.02606	629.04	1467.53	2.3377	4.6789	2.058
90	5.11670	482.8	0.02300	658.61	1459.19	2.4168	4.6213	2.187
95	5.66430	470.2	0.02027	689.19	1449.01	2.4973	4.5612	2.349
100	6.25530	456.6	0.01782	721.00	1436.63	2.5797	4.4975	2.562
105	6.89230	441.9	0.01561	754.35	1421.57	2.6647	4.4291	2.851
110	7.57830	425.6	0.01360	789.68	1403.08	2.7533	4.3542	3.26
115	8.31700	407.2	0.01174	827.74	1379.99	2.8474	4.2702	3.91
120	9.11250	385.5	0.00999	869.92	1350.23	2.9502	4.1719	5.04
125	9.97002	357.8	0.00828	919.68	1309.12	3.0702	4.0483	7.62
130	10.89770	312.3	0.00638	992.02	1239.32	3.2437	3.8571	20.66
132.25[c]	11.33300	225.0	0.00444	1119.22	1119.22	3.5542	3.5542	∞

*Temperatures on ITS-90 scale [a]Triple point [b]Normal boiling point [c]Critical point

Refrigerants

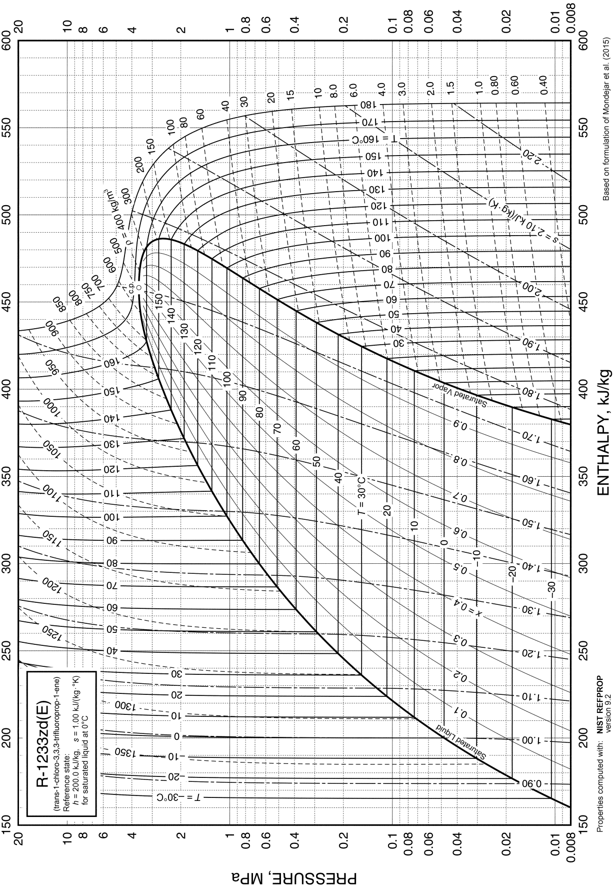


Figure 8.10 Pressure-Enthalpy Diagram for Refrigerant 1233zd(E) [2017F, Ch 30, Fig 12]

Table 8.13 Refrigerant 1233zd(E) (trans-1-chloro-3,3,3-trifluoroprop-1-ene) Properties of Saturated Liquid and Saturated Vapor [2017F, Ch 30, Tbl R-1234zd(E)]

Temp., °C	Pressure, MPa	Density, kg/m³ Liquid	Volume, m³/kg Vapor	Enthalpy, kJ/kg		Entropy, kJ/(kg·K)		Specific Heat c_p, kJ/(kg·K)		c_p/c_v Vapor
				Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	
–50	0.00289	1429.8	4.9048	142.87	369.48	0.7694	1.7849	1.109	0.660	1.108
–45	0.00410	1419.3	3.5348	148.43	372.76	0.7940	1.7773	1.115	0.672	1.107
–40	0.00570	1408.7	2.5918	154.02	376.08	0.8182	1.7707	1.122	0.683	1.105
–35	0.00781	1398.1	1.9310	159.65	379.43	0.8421	1.7650	1.128	0.694	1.104
–30	0.01052	1387.4	1.4601	165.31	382.82	0.8656	1.7602	1.135	0.704	1.104
–25	0.01398	1376.6	1.1193	171.00	386.24	0.8888	1.7561	1.142	0.715	1.103
–20	0.01833	1365.7	0.86907	176.73	389.68	0.9116	1.7528	1.149	0.726	1.103
–18	0.02035	1361.3	0.78804	179.03	391.06	0.9207	1.7517	1.152	0.730	1.102
–16	0.02256	1357.0	0.71589	181.34	392.45	0.9297	1.7506	1.154	0.734	1.102
–14	0.02495	1352.6	0.65150	183.65	393.83	0.9386	1.7497	1.157	0.739	1.102
–12	0.02755	1348.1	0.59392	185.97	395.22	0.9475	1.7488	1.160	0.743	1.102
–10	0.03036	1343.7	0.54235	188.29	396.62	0.9564	1.7480	1.163	0.747	1.103
–8	0.03340	1339.3	0.49606	190.62	398.01	0.9652	1.7473	1.166	0.751	1.103
–6	0.03668	1334.8	0.45444	192.96	399.41	0.9740	1.7467	1.169	0.756	1.103
–4	0.04021	1330.3	0.41695	195.30	400.80	0.9827	1.7462	1.171	0.760	1.103
–2	0.04402	1325.8	0.38313	197.65	402.20	0.9914	1.7458	1.174	0.764	1.103
0	0.04811	1321.3	0.35257	200.00	403.60	1.0000	1.7454	1.177	0.769	1.104
2	0.05250	1316.7	0.32490	202.36	405.00	1.0086	1.7451	1.180	0.773	1.104
4	0.05720	1312.2	0.29981	204.72	406.40	1.0171	1.7448	1.183	0.778	1.104
6	0.06224	1307.6	0.27702	207.10	407.80	1.0257	1.7447	1.186	0.782	1.105
8	0.06762	1303.0	0.25630	209.47	409.21	1.0341	1.7445	1.189	0.787	1.105
10	0.07337	1298.3	0.23743	211.86	410.61	1.0426	1.7445	1.192	0.791	1.106
12	0.07949	1293.7	0.22022	214.25	412.01	1.0510	1.7445	1.195	0.796	1.106
14	0.08601	1289.0	0.20449	216.64	413.41	1.0593	1.7445	1.198	0.801	1.107
16	0.09295	1284.3	0.19011	219.04	414.81	1.0676	1.7447	1.201	0.805	1.108
18	0.10032	1279.6	0.17694	221.45	416.20	1.0759	1.7448	1.205	0.810	1.108
18.26[b]	0.10132	1278.9	0.17529	221.77	416.39	1.0770	1.7448	1.205	0.811	1.108
20	0.10815	1274.8	0.16486	223.87	417.60	1.0841	1.7450	1.208	0.815	1.109
22	0.11644	1270.0	0.15376	226.29	419.00	1.0924	1.7453	1.211	0.820	1.110
24	0.12522	1265.2	0.14356	228.72	420.39	1.1005	1.7456	1.214	0.825	1.111
26	0.13452	1260.4	0.13417	231.15	421.78	1.1087	1.7459	1.218	0.830	1.112
28	0.14434	1255.5	0.12552	233.59	423.17	1.1168	1.7463	1.221	0.835	1.113
30	0.15471	1250.6	0.11753	236.04	424.56	1.1249	1.7467	1.224	0.840	1.114
32	0.16566	1245.7	0.11015	238.50	425.94	1.1329	1.7472	1.228	0.845	1.115
34	0.17719	1240.7	0.10333	240.96	427.32	1.1409	1.7477	1.231	0.850	1.116
36	0.18934	1235.7	0.09702	243.43	428.70	1.1489	1.7482	1.235	0.856	1.117
38	0.20212	1230.7	0.09116	245.91	430.08	1.1569	1.7488	1.238	0.861	1.119
40	0.21555	1225.6	0.08573	248.39	431.45	1.1648	1.7493	1.242	0.866	1.120
42	0.22966	1220.5	0.08069	250.88	432.81	1.1727	1.7500	1.246	0.872	1.122
44	0.24447	1215.4	0.07600	253.38	434.18	1.1805	1.7506	1.250	0.878	1.123
46	0.26000	1210.2	0.07163	255.89	435.54	1.1884	1.7513	1.254	0.884	1.125
48	0.27628	1205.0	0.06757	258.40	436.89	1.1962	1.7520	1.258	0.889	1.127
50	0.29332	1199.7	0.06378	260.93	438.24	1.2040	1.7527	1.262	0.895	1.128
52	0.31116	1194.4	0.06024	263.46	439.59	1.2117	1.7534	1.266	0.902	1.130
54	0.32981	1189.1	0.05693	266.00	440.93	1.2195	1.7542	1.270	0.908	1.132
56	0.34929	1183.7	0.05385	268.55	442.26	1.2272	1.7550	1.274	0.914	1.134
58	0.36964	1178.3	0.05096	271.10	443.59	1.2349	1.7558	1.279	0.921	1.137
60	0.39088	1172.8	0.04825	273.67	444.91	1.2426	1.7566	1.283	0.927	1.139
62	0.41303	1167.2	0.04571	276.24	446.23	1.2502	1.7574	1.288	0.934	1.142
64	0.43612	1161.7	0.04333	278.83	447.54	1.2578	1.7582	1.293	0.941	1.144
66	0.46017	1156.0	0.04110	281.42	448.84	1.2655	1.7591	1.298	0.948	1.147
68	0.48521	1150.3	0.03900	284.03	450.14	1.2730	1.7600	1.303	0.955	1.150
70	0.51126	1144.6	0.03702	286.64	451.43	1.2806	1.7608	1.308	0.963	1.153
72	0.53835	1138.8	0.03517	289.26	452.70	1.2882	1.7617	1.313	0.970	1.156
74	0.56651	1132.9	0.03342	291.90	453.98	1.2957	1.7626	1.319	0.978	1.159
76	0.59576	1127.0	0.03177	294.54	455.24	1.3032	1.7635	1.324	0.986	1.163
78	0.62613	1121.0	0.03021	297.20	456.49	1.3107	1.7644	1.330	0.995	1.167
80	0.65765	1114.9	0.02875	299.86	457.73	1.3182	1.7653	1.336	1.003	1.171
90	0.83345	1083.4	0.02253	313.38	463.78	1.3555	1.7697	1.370	1.050	1.195
100	1.0423	1049.7	0.01778	327.24	469.49	1.3926	1.7739	1.412	1.107	1.227
110	1.2880	1013.1	0.01408	341.51	474.77	1.4297	1.7775	1.465	1.179	1.273
120	1.5750	972.6	0.01116	356.29	479.44	1.4671	1.7803	1.538	1.277	1.342
130	1.9080	926.9	0.00881	371.74	483.27	1.5050	1.7816	1.643	1.423	1.455
140	2.2928	873.1	0.00687	388.12	485.81	1.5441	1.7805	1.819	1.675	1.661
150	2.7364	805.4	0.00522	406.03	486.16	1.5856	1.7750	2.193	2.232	2.141
160	3.2485	704.0	0.00368	427.43	481.49	1.6340	1.7588	3.751	4.545	4.191
166.45[c]	3.6237	480.2	0.00208	458.27	458.27	1.7032	1.7032	∞	∞	∞

[b]Normal boiling point

[c]Critical point

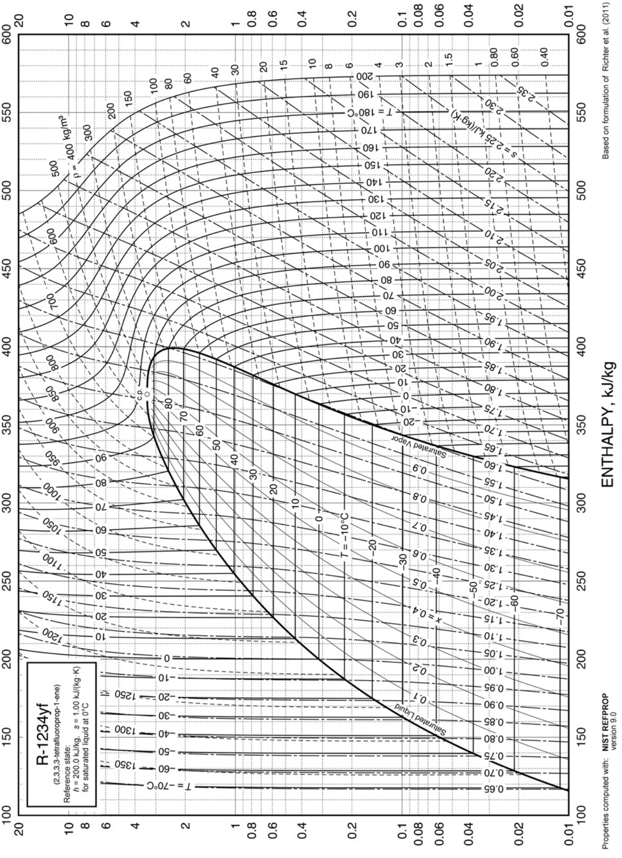


Figure 8.11 Pressure-Enthalpy Diagram for Refrigerant 1234yf [2017F, Ch 30, Fig 13]

Table 8.14 Refrigerant 1234yf (2,3,3,3-tetrafluoroprop-1-ene) Properties of Saturated Liquid and Saturated Vapor [2017F, Ch 30, Tbl R-1234yf]

Temp., °C	Pressure, MPa	Density, kg/m³ Liquid	Volume, m³/kg Vapor	Enthalpy, kJ/kg Liquid	Enthalpy, kJ/kg Vapor	Entropy, kJ/(kg·K) Liquid	Entropy, kJ/(kg·K) Vapor	Specific Heat c_p, kJ/(kg·K) Liquid	Specific Heat c_p, kJ/(kg·K) Vapor	c_p/c_v Vapor
–50	0.03742	1318.4	0.42472	139.63	329.85	0.7573	1.6098	1.128	0.746	1.124
–45	0.04862	1305.2	0.33259	145.31	333.21	0.7825	1.6060	1.143	0.762	1.125
–40	0.06237	1291.9	0.26354	151.07	336.58	0.8074	1.6031	1.157	0.778	1.126
–35	0.07904	1278.3	0.21110	156.90	339.95	0.8321	1.6007	1.173	0.794	1.127
–30	0.09906	1264.5	0.17079	162.81	343.32	0.8566	1.5990	1.188	0.811	1.129
–29.49[b]	0.10132	1263.1	0.16719	163.42	343.67	0.8591	1.5988	1.190	0.813	1.129
–28	0.10810	1259.0	0.15732	165.20	344.67	0.8663	1.5984	1.195	0.818	1.130
–26	0.11778	1253.4	0.14512	167.60	346.02	0.8760	1.5980	1.201	0.825	1.131
–24	0.12812	1247.7	0.13404	170.01	347.36	0.8857	1.5976	1.207	0.832	1.132
–22	0.13916	1242.0	0.12398	172.43	348.71	0.8954	1.5973	1.214	0.839	1.133
–20	0.15092	1236.3	0.11482	174.87	350.05	0.9050	1.5970	1.220	0.847	1.135
–18	0.16344	1230.5	0.10647	177.32	351.39	0.9146	1.5968	1.227	0.854	1.136
–16	0.17676	1224.7	0.09884	179.79	352.73	0.9242	1.5967	1.234	0.862	1.137
–14	0.19090	1218.8	0.09187	182.27	354.06	0.9338	1.5967	1.240	0.869	1.139
–12	0.20590	1212.9	0.08548	184.76	355.39	0.9433	1.5967	1.247	0.877	1.141
–10	0.22178	1207.0	0.07962	187.26	356.72	0.9528	1.5968	1.254	0.885	1.142
–8	0.23860	1200.9	0.07424	189.78	358.04	0.9623	1.5969	1.261	0.893	1.144
–6	0.25637	1194.9	0.06930	192.31	359.36	0.9717	1.5970	1.268	0.901	1.146
–4	0.27514	1188.7	0.06474	194.86	360.68	0.9812	1.5973	1.275	0.909	1.149
–2	0.29495	1182.5	0.06054	197.42	361.99	0.9906	1.5975	1.282	0.918	1.151
0	0.31582	1176.3	0.05667	200.00	363.29	1.0000	1.5978	1.289	0.926	1.153
2	0.33780	1170.0	0.05309	202.59	364.59	1.0094	1.5981	1.297	0.935	1.156
4	0.36092	1163.6	0.04977	205.20	365.88	1.0187	1.5985	1.304	0.944	1.159
6	0.38523	1157.2	0.04670	207.82	367.16	1.0281	1.5989	1.312	0.953	1.162
8	0.41075	1150.6	0.04385	210.45	368.44	1.0374	1.5993	1.320	0.962	1.165
10	0.43753	1144.0	0.04121	213.10	369.70	1.0467	1.5998	1.327	0.972	1.168
12	0.46561	1137.4	0.03875	215.77	370.96	1.0560	1.6003	1.335	0.982	1.172
14	0.49503	1130.6	0.03646	218.45	372.21	1.0653	1.6008	1.344	0.992	1.176
16	0.52583	1123.8	0.03433	221.15	373.45	1.0746	1.6013	1.352	1.002	1.180
18	0.55804	1116.9	0.03235	223.87	374.67	1.0838	1.6018	1.361	1.013	1.185
20	0.59172	1109.9	0.03049	226.60	375.89	1.0931	1.6024	1.369	1.024	1.190
22	0.62690	1102.8	0.02876	229.34	377.09	1.1023	1.6029	1.378	1.035	1.195
24	0.66363	1095.5	0.02714	232.11	378.28	1.1115	1.6034	1.387	1.047	1.201
26	0.70194	1088.2	0.02562	234.89	379.45	1.1208	1.6040	1.397	1.060	1.207
28	0.74189	1080.8	0.02420	237.69	380.61	1.1300	1.6045	1.407	1.073	1.213
30	0.78351	1073.3	0.02287	240.51	381.75	1.1392	1.6051	1.417	1.086	1.220
32	0.82686	1065.7	0.02162	243.35	382.87	1.1484	1.6056	1.427	1.101	1.228
34	0.87197	1057.9	0.02044	246.21	383.98	1.1576	1.6061	1.438	1.116	1.236
36	0.91890	1050.0	0.01934	249.09	385.06	1.1668	1.6066	1.449	1.132	1.245
38	0.96769	1042.0	0.01830	251.98	386.13	1.1759	1.6071	1.461	1.149	1.254
40	1.0184	1033.8	0.01732	254.90	387.17	1.1851	1.6075	1.473	1.167	1.265
42	1.0711	1025.5	0.01639	257.84	388.19	1.1943	1.6079	1.486	1.186	1.276
44	1.1257	1017.0	0.01552	260.81	389.18	1.2035	1.6083	1.500	1.207	1.289
46	1.1825	1008.3	0.01469	263.80	390.14	1.2128	1.6087	1.515	1.229	1.302
48	1.2413	999.4	0.01392	266.81	391.08	1.2220	1.6089	1.531	1.252	1.317
50	1.3023	990.4	0.01318	269.85	391.98	1.2312	1.6092	1.548	1.277	1.333
52	1.3656	981.1	0.01248	272.92	392.85	1.2405	1.6094	1.566	1.305	1.351
54	1.4311	971.6	0.01182	276.02	393.68	1.2498	1.6095	1.586	1.335	1.371
56	1.4989	961.8	0.01119	279.15	394.48	1.2592	1.6095	1.607	1.367	1.393
58	1.5692	951.7	0.01059	282.32	395.23	1.2685	1.6095	1.631	1.403	1.418
60	1.6419	941.3	0.01002	285.53	395.93	1.2779	1.6093	1.656	1.442	1.445
62	1.7171	930.6	0.00948	288.77	396.58	1.2874	1.6091	1.685	1.485	1.477
64	1.7949	919.5	0.00897	292.06	397.18	1.2969	1.6087	1.717	1.534	1.512
66	1.8754	907.9	0.00848	295.39	397.71	1.3065	1.6082	1.752	1.589	1.553
68	1.9586	895.8	0.00801	298.78	398.18	1.3162	1.6076	1.792	1.651	1.600
70	2.0445	883.2	0.00756	302.22	398.57	1.3260	1.6068	1.837	1.724	1.655
72	2.1334	870.0	0.00712	305.72	398.87	1.3359	1.6058	1.890	1.808	1.719
74	2.2252	856.1	0.00671	309.30	399.07	1.3459	1.6045	1.951	1.907	1.797
76	2.3201	841.4	0.00631	312.95	399.16	1.3561	1.6030	2.025	2.028	1.891
78	2.4181	825.7	0.00592	316.69	399.11	1.3664	1.6011	2.114	2.176	2.009
80	2.5194	809.0	0.00555	320.54	398.90	1.3770	1.5989	2.227	2.364	2.158
85	2.7879	760.4	0.00464	330.81	397.40	1.4049	1.5909	2.702	3.168	2.803
90	3.0803	694.1	0.00372	342.79	393.32	1.4370	1.5762	4.186	5.688	4.820
94.70[c]	3.3822	475.6	0.00210	369.55	369.55	1.5087	1.5087	∞	∞	∞

[b]Normal boiling point [c]Critical point

Refrigerants

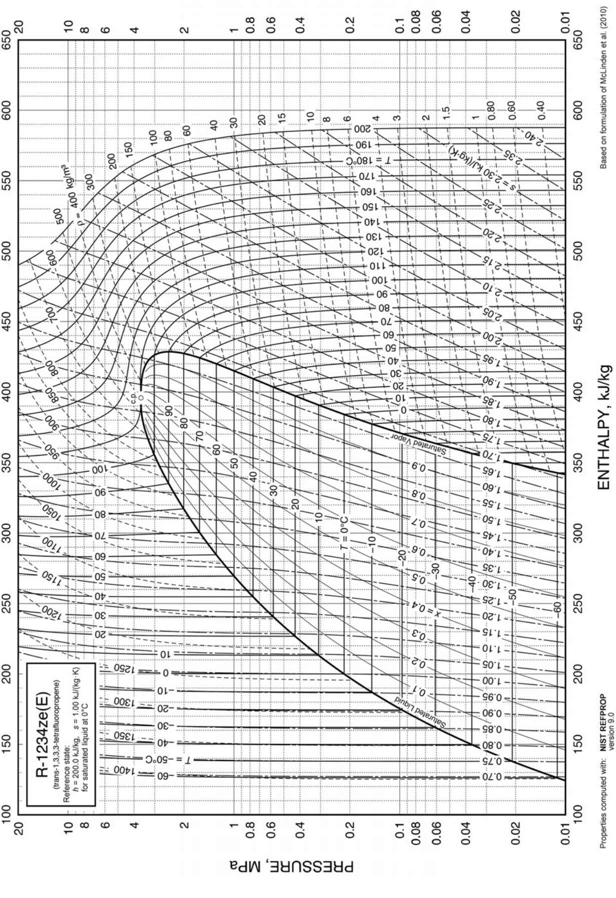


Figure 8.12 Pressure-Enthalpy Diagram for Refrigerant 1234ze(E) [2017F, Ch 30, Fig 14]

Table 8.15 Refrigerant 1234ze(E) (Trans-1,3,3,3-Tetrafluoropropene) Properties of Saturated Liquid and Saturated Vapor [2017F, Ch 30, Tbl R-1234ze(E)

Temp., °C	Pressure, MPa	Density, kg/m^3 Liquid	Volume, m^3/kg Vapor	Enthalpy, kJ/kg Liquid	Enthalpy, kJ/kg Vapor	Entropy, kJ/(kg·K) Liquid	Entropy, kJ/(kg·K) Vapor	Specific Heat c_p, kJ/(kg·K) Liquid	Specific Heat c_p, kJ/(kg·K) Vapor	c_p/c_v Vapor
–50	0.02092	1375.3	0.76762	136.20	348.81	0.7429	1.6956	1.240	0.755	1.115
–45	0.02793	1362.4	0.58586	142.42	352.37	0.7704	1.6907	1.246	0.766	1.115
–40	0.03675	1349.5	0.45337	148.66	355.94	0.7975	1.6865	1.251	0.777	1.115
–35	0.04768	1336.5	0.35533	154.94	359.51	0.8241	1.6831	1.258	0.789	1.116
–30	0.06109	1323.3	0.28176	161.25	363.09	0.8503	1.6803	1.265	0.801	1.117
–25	0.07735	1309.9	0.22584	167.60	366.65	0.8761	1.6782	1.272	0.814	1.118
–20	0.09687	1296.4	0.18282	173.99	370.20	0.9015	1.6766	1.280	0.826	1.120
–18.97[b]	0.10132	1293.6	0.17525	175.31	370.93	0.9067	1.6763	1.282	0.829	1.121
–18	0.10569	1290.9	0.16843	176.56	371.62	0.9116	1.6761	1.284	0.832	1.121
–16	0.11512	1285.4	0.15540	179.13	373.03	0.9216	1.6756	1.287	0.837	1.122
–14	0.12520	1279.9	0.14357	181.71	374.44	0.9316	1.6752	1.291	0.843	1.123
–12	0.13596	1274.3	0.13281	184.30	375.85	0.9415	1.6749	1.294	0.848	1.125
–10	0.14744	1268.7	0.12302	186.90	377.25	0.9513	1.6747	1.298	0.854	1.126
–8	0.15965	1263.1	0.11409	189.50	378.64	0.9612	1.6745	1.302	0.860	1.127
–6	0.17263	1257.4	0.10593	192.11	380.04	0.9709	1.6744	1.306	0.865	1.128
–4	0.18642	1251.7	0.09847	194.73	381.42	0.9807	1.6743	1.310	0.871	1.130
–2	0.20105	1245.9	0.09163	197.36	382.80	0.9904	1.6743	1.314	0.877	1.132
0	0.21655	1240.1	0.08537	200.00	384.18	1.0000	1.6743	1.318	0.884	1.133
2	0.23296	1234.3	0.07961	202.65	385.55	1.0096	1.6743	1.323	0.890	1.135
4	0.25031	1228.4	0.07431	205.30	386.91	1.0192	1.6744	1.327	0.897	1.137
6	0.26863	1222.4	0.06944	207.97	388.27	1.0287	1.6746	1.332	0.903	1.139
8	0.28797	1216.4	0.06494	210.64	389.62	1.0382	1.6748	1.337	0.910	1.141
10	0.30836	1210.4	0.06079	213.32	390.96	1.0476	1.6750	1.342	0.917	1.144
12	0.32983	1204.3	0.05695	216.02	392.29	1.0571	1.6752	1.347	0.924	1.146
14	0.35243	1198.1	0.05340	218.72	393.61	1.0664	1.6755	1.353	0.932	1.149
16	0.37619	1191.9	0.05012	221.44	394.93	1.0758	1.6758	1.358	0.939	1.152
18	0.40114	1185.6	0.04707	224.16	396.23	1.0851	1.6761	1.364	0.947	1.155
20	0.42734	1179.3	0.04423	226.90	397.53	1.0944	1.6765	1.370	0.955	1.158
22	0.45482	1172.8	0.04160	229.65	398.81	1.1037	1.6768	1.376	0.963	1.161
24	0.48362	1166.4	0.03915	232.41	400.09	1.1129	1.6772	1.382	0.971	1.165
26	0.51377	1159.8	0.03687	235.19	401.35	1.1221	1.6776	1.389	0.980	1.169
28	0.54533	1153.2	0.03475	237.98	402.60	1.1313	1.6780	1.396	0.989	1.173
30	0.57833	1146.4	0.03276	240.78	403.83	1.1405	1.6784	1.403	0.999	1.177
32	0.61281	1139.6	0.03091	243.59	405.06	1.1497	1.6788	1.410	1.008	1.181
34	0.64882	1132.8	0.02918	246.42	406.27	1.1588	1.6792	1.418	1.018	1.186
36	0.68640	1125.8	0.02755	249.27	407.46	1.1679	1.6796	1.426	1.029	1.192
38	0.72560	1118.7	0.02603	252.13	408.64	1.1770	1.6801	1.434	1.039	1.197
40	0.76645	1111.5	0.02461	255.00	409.80	1.1861	1.6805	1.443	1.051	1.203
42	0.80901	1104.2	0.02327	257.89	410.95	1.1952	1.6809	1.452	1.063	1.210
44	0.85332	1096.8	0.02202	260.80	412.07	1.2043	1.6813	1.462	1.075	1.217
46	0.89943	1089.3	0.02084	263.73	413.18	1.2134	1.6816	1.472	1.088	1.224
48	0.94738	1081.6	0.01972	266.68	414.26	1.2224	1.6820	1.482	1.101	1.232
50	0.99722	1073.8	0.01868	269.64	415.33	1.2315	1.6823	1.493	1.116	1.241
52	1.0490	1065.9	0.01769	272.63	416.37	1.2405	1.6826	1.505	1.131	1.250
54	1.1028	1057.8	0.01676	275.63	417.38	1.2496	1.6829	1.517	1.147	1.260
56	1.1586	1049.5	0.01588	278.66	418.37	1.2587	1.6831	1.530	1.165	1.272
58	1.2165	1041.1	0.01505	281.71	419.33	1.2677	1.6833	1.544	1.184	1.284
60	1.2766	1032.5	0.01427	284.78	420.26	1.2768	1.6835	1.558	1.204	1.297
62	1.3388	1023.7	0.01353	287.88	421.16	1.2859	1.6836	1.574	1.225	1.312
64	1.4033	1014.7	0.01282	291.01	422.03	1.2950	1.6836	1.591	1.249	1.328
66	1.4702	1005.5	0.01216	294.16	422.86	1.3041	1.6836	1.609	1.274	1.345
68	1.5393	996.0	0.01152	297.34	423.65	1.3133	1.6835	1.628	1.302	1.365
70	1.6110	986.2	0.01092	300.56	424.40	1.3225	1.6834	1.649	1.333	1.386
72	1.6851	976.2	0.01035	303.80	425.10	1.3317	1.6831	1.672	1.367	1.411
74	1.7617	965.9	0.00980	307.09	425.76	1.3410	1.6828	1.698	1.404	1.438
76	1.8410	955.2	0.00929	310.41	426.36	1.3503	1.6824	1.726	1.445	1.468
78	1.9230	944.1	0.00879	313.77	426.90	1.3596	1.6818	1.757	1.492	1.503
80	2.0077	932.7	0.00832	317.19	427.38	1.3691	1.6811	1.792	1.545	1.542
85	2.2321	901.9	0.00722	325.95	428.25	1.3930	1.6787	1.901	1.712	1.671
90	2.4755	867.2	0.00623	335.12	428.52	1.4177	1.6749	2.062	1.963	1.868
95	2.7395	826.9	0.00531	344.89	427.93	1.4435	1.6691	2.327	2.386	2.206
100	3.0260	777.3	0.00444	355.59	425.95	1.4715	1.6600	2.859	3.258	2.905
105	3.3378	708.1	0.00356	368.23	421.12	1.5040	1.6438	4.573	6.122	5.179
109.36[c]	3.6349	489.2	0.00204	395.54	395.54	1.5744	1.5744	∞	∞	∞

[b]Normal boiling point

[c]Critical point

Table 8.16 Comparative Refrigerant Performance per Kilowatt of Refrigeration [2017F, Ch 29, Tbl 8]

Refrigerant No.	Chemical Name or Composition (% by mass)	Evaporator Pressure, MPa	Condenser Pressure, MPa	Compression Ratio	Net Refrigerating Effect, kJ/kg	Refrigerant Circulated, g/s	Liquid Circulated, L/s	Specific Volume of Suction Gas, m^3/kg	Compressor Displacement, L/s	Power Consumption, kW	Coefficient of Performance	Compressor Discharge Temp., °C
Evaporator –31.7°C/Condenser 30°C												
744	Carbon dioxide	1.349	7.213	5.35	132.1	7.57	0.0128	0.0285	0.2160	0.5892	1.698	91.3
170	Ethane	1.012	4.655	4.6	153.6	6.51	0.0236	0.0548	0.3567	0.5947	1.681	57.9
1270	Propylene	0.199	1.305	6.57	269.1	3.72	0.0075	0.2266	0.8422	0.3471	2.88	49.1
507A	R-125/143a (50/50)	0.199	1.460	7.34	101.1	9.89	0.0097	0.0949	0.9360	0.3887	2.573	38.1
404A	R-125/143a/134a (44/52/4)	0.190	1.421	7.46	104.9	9.54	0.0093	0.1005	0.9565	0.3853	2.595	38.9
502	R-22/115 (48.8/51.2)	0.183	1.304	7.14	97.8	10.22	0.0086	0.0924	0.9470	0.3651	2.739	41.3
22	Chlorodifluoromethane	0.152	1.192	7.81	155.3	6.44	0.0055	0.1448	0.9326	0.3369	2.967	65.4
717	Ammonia	0.110	1.167	10.61	1079.1	0.93	0.0016	1.0425	0.9643	0.3327	3.007	140.9
Evaporator –6.7°C/Condenser 30°C												
744	Carbon dioxide	2.909	7.213	2.48	129.5	7.72	0.0130	0.0127	0.0977	0.2845	3.514	61.3
170	Ethane	2.024	4.655	2.3	163.1	6.13	0.0222	0.0263	0.1612	0.2786	3.588	46.6
32	Difluoromethane	0.653	1.928	2.95	258.6	3.87	0.0041	0.0563	0.2178	0.1690	5.924	59.7
410A	R-32/125 (50/50)	0.643	1.886	2.94	170.9	5.85	0.0057	0.0406	0.2381	0.1728	5.78	46.6
507A	R-125/143a (50/50)	0.503	1.460	2.9	114.9	8.70	0.0085	0.0385	0.3349	0.1798	5.564	34.2
404A	R-125/143a/134a (44/52/4)	0.486	1.421	2.92	118.8	8.42	0.0083	0.0405	0.3410	0.1785	5.598	34.6
1270	Propylene	0.476	1.305	2.74	294.4	3.40	0.0068	0.0986	0.3359	0.1675	5.975	39.3
502	R-22/115 (48.8/51.2)	0.457	1.304	2.86	109.5	9.13	0.0077	0.0386	0.3527	0.1724	5.799	35.4
22	Chlorodifluoromethane	0.399	1.192	2.99	165.9	6.03	0.0051	0.0584	0.3520	0.1637	6.105	47.8
407C	R-32/125/134a (23/25/52)	0.396	1.267	3.19	167.1	5.98	0.0053	0.0588	0.3518	0.1686	5.93	43.9
290	Propane	0.385	1.079	2.8	288.6	3.47	0.0072	0.1180	0.4093	0.1669	5.987	34.9
717	Ammonia	0.332	1.167	3.51	1113.0	0.90	0.0015	0.3689	0.3313	0.1599	6.254	82.1
1234yf	2,3,3,3-Tetrafluoropropene*	0.250	0.783	3.13	120.5	8.30	0.0077	0.0718	0.5954	0.1715	5.835	30.0

Table 8.16 Comparative Refrigerant Performance per Kilowatt of Refrigeration [2017F, Ch 29, Tbl 8] ***(Continued)***

Refrigerant		Evaporator Pressure, MPa	Condenser Pressure, MPa	Com-pression Ratio	Net Refrigerating Effect, kJ/kg	Refrigerant Circulated, g/s	Liquid Circulated, L/s	Specific Volume of Suction Gas, m^3/kg	Compressor Displacement, L/s	Power Consump-tion, kW	Coefficient of Performance	Com-pressor Discharge Temp., °C
No.	Chemical Name or Composition (% by mass)											
134a	Tetrafluoroethane	0.228	0.770	3.37	153.0	6.54	0.0055	0.0880	0.5745	0.1650	6.063	34.8
1234ze(E)	trans-1,3,3,3-Tetrafluoropropene*	0.168	0.578	3.44	139.6	7.16	0.0063	0.1086	0.7798	0.1658	6.03	30.0
600a	Isobutane*	0.123	0.405	3.29	278.0	3.60	0.0066	0.2984	1.0723	0.1620	6.171	30.0
Evaporator 7.2°C/Condenser 30°C												
32	Difluoromethane	1.018	1.928	1.89	261.1	3.83	0.0040	0.0360	0.1381	0.0944	10.602	46.9
410A	R-32/125 (50/50)	1.000	1.886	1.89	175.0	5.71	0.0055	0.0260	0.1484	0.0965	10.379	39.8
502	R-22/115 (48.8/51.2)	0.703	1.304	1.85	115.3	8.67	0.0073	0.0252	0.2187	0.0956	10.474	33.2
407C	R-32/125/134a (23/25/52)	0.640	1.267	1.98	173.7	5.76	0.0051	0.0367	0.2112	0.0939	10.655	39.3
22	Chlorodifluoromethane	0.626	1.192	1.9	171.0	5.85	0.0050	0.0377	0.2205	0.0918	10.885	40.3
290	Propane	0.588	1.079	1.84	303.9	3.29	0.0068	0.0787	0.2580	0.0931	10.743	32.6
717	Ammonia	0.558	1.167	2.09	1127.8	0.89	0.0015	0.2254	0.1998	0.0893	11.186	58.6
500	R-12/152a (73.8/26.2)	0.458	0.880	1.92	150.4	6.65	0.0059	0.0453	0.3010	0.0916	10.925	34.6
1234yf	2,3,3,3-Tetrafluoropropene*	0.401	0.783	1.96	129.0	7.75	0.0072	0.0453	0.3514	0.0941	10.623	30.0
12	Dichlorodifluoromethane	0.388	0.744	1.92	126.9	7.88	0.0061	0.0449	0.3536	0.0910	11.004	33.1
134a	Tetrafluoroethane	0.377	0.770	2.04	161.0	6.21	0.0052	0.0542	0.3364	0.0918	10.903	32.6
1234ze(E)	trans-1,3,3,3-Tetrafluoropropene*	0.280	0.578	2.06	149.1	6.71	0.0059	0.0668	0.4483	0.0918	10.899	30.0
600a	Isobutane*	0.201	0.405	2.01	296.3	3.37	0.0062	0.1879	0.6332	0.0901	11.084	30.0
600	Butane*	0.134	0.283	2.11	326.9	3.06	0.0054	0.2853	0.8725	0.0891	11.226	30.0
123	Dichlorotrifluoroethane	0.045	0.110	2.44	155.5	6.43	0.0044	0.3309	2.1269	0.0878	11.397	30.0
113	Trichlorotrifluoroethane*	0.021	0.054	2.57	137.6	7.27	0.0047	0.5874	4.2686	0.0876	11.409	30.0

*Superheat required
Data from NIST CYCLE_D 4.0, zero subcool, zero superheat unless noted, no line losses, 100% efficiencies, average temperatures.

Table 8.17 Suction, Discharge, and Liquid Line Capacities in Kilowatts for Refrigerant 404A (Single- or High-Stage Applications)

[2014R, Ch 1, Tbl 6]

Line Size	Suction Lines (Δt = 0.04 K/m)						Discharge Lines (Δt = 0.02 K/m, Δp = 74.90)						Liquid Lines (40°C)		
	Saturated Suction Temperature, °C						Saturated Suction Temperature, °C						See note a		
Type L Copper, OD, mm	–50	–40	–30	–20	–5	5	–50	–40	–30	–20	–5	5	Velocity = 0.5 m/s	Δt = 0.02 K/m Drop	Δt = 0.05 K/m Drop
	Corresponding Δp, Pa/m						Corresponding Δp, Pa/m								
	165.5	240.6	337.2	455.1	679.1	863.2	875.6	875.6	875.6	875.6	875.6	875.6		Δp = 875.6	Δp = 2189.1
12	0.16	0.27	0.43	0.67	1.19	1.69	1.73	1.87	2.00	2.13	2.31	2.42	4.1	8.0	13.3
15	0.30	0.52	0.83	1.28	2.27	3.22	3.29	3.55	3.81	4.05	4.40	4.61	6.7	15.3	25.2
18	0.53	0.90	1.45	2.22	3.94	5.57	5.71	6.16	6.59	7.02	7.62	7.99	10.1	26.6	43.7
22	0.94	1.59	2.55	3.91	6.93	9.79	10.00	10.79	11.56	12.30	13.36	14.01	15.5	46.8	76.7
28	1.86	3.14	5.04	7.72	13.66	19.25	19.68	21.23	22.74	24.21	26.29	27.57	26.0	92.5	151.1
35	3.43	5.78	9.26	14.15	25.00	35.17	35.96	38.78	41.54	44.23	48.03	50.37	41.1	169.3	276.3
42	5.71	9.61	15.36	23.46	41.32	58.16	59.48	64.15	68.72	73.16	79.45	83.32	60.3	280.4	456.2
54	11.37	19.12	30.50	46.57	81.90	114.98	117.62	126.86	135.89	144.67	157.11	164.76	101.4	556.9	903.2
67	20.31	34.10	54.30	82.75	145.45	203.96	208.67	225.07	241.08	256.66	278.73	292.29	157.3	989.8	1601.8
79	31.54	52.78	84.12	128.09	224.52	314.97	321.69	346.97	371.66	395.67	429.70	450.60	219.3	1529.9	2473.4
105	67.66	113.08	179.89	273.26	478.70	670.69	685.09	738.92	791.51	842.65	915.11	959.63	391.5	3264.9	5265.6
130	120.40	201.19	319.22	484.40	847.54	1188.02	1213.68	1309.04	1402.20	1492.80	1621.17	1700.03	607.3	5788.8	9335.2
156	195.94	326.58	518.54	785.73	1372.94	1921.03	1962.62	2116.83	2267.48	2413.98	2621.57	2749.09	879.6	9382.5	15 109.7
206	401.89	669.47	1059.73	1607.24	2805.00	3917.77	4003.19	4317.73	4625.02	4923.84	5347.26	5607.37	1522.1	19 177.4	30 811.3
257	715.93	1189.91	1885.42	2851.68	4974.31	6949.80	7084.63	7641.29	8185.11	8713.94	9463.30	9923.61	2366.6	33 992.3	54 651.2

Table 8.17 Suction, Discharge, and Liquid Line Capacities in Kilowatts for Refrigerant 404A (Single- or High-Stage Applications) [2014R, Ch 1, Tbl 6] ***(Continued)***

Line Size		Suction Lines (Δt = 0.04 K/m)						Discharge Lines (Δt = 0.02 K/m, Δp = 74.90)						Liquid Lines (40°C)		
		Saturated Suction Temperature, °C						Saturated Suction Temperature, °C						See note a		
		–50	–40	–30	–20	–5	5	–50	–40	–30	–20	–5	5	Velocity = 0.5 m/s	Δt = 0.02 K/m Drop	Δt = 0.05 K/m Drop
		Corresponding Δp, Pa/m						Corresponding Δp, Pa/m								
		165.5	240.6	337.2	455.1	679.1	863.2	875.6	875.6	875.6	875.6	875.6	875.6		Δp = 875.6	Δp = 2189.1
Steel																
mm	SCH															
10	80	0.16	0.26	0.40	0.61	1.05	1.46	1.49	1.61	1.72	1.83	1.99	2.09	4.6	7.2	11.5
15	80	0.31	0.51	0.80	1.20	2.07	2.88	2.94	3.17	3.39	3.61	3.92	4.12	7.6	14.3	22.7
20	80	0.70	1.15	1.80	2.70	4.66	6.48	6.61	7.13	7.64	8.14	8.84	9.27	14.1	32.1	51.1
25	80	1.37	2.25	3.53	5.30	9.13	12.68	12.95	13.97	14.96	15.93	17.30	18.14	23.4	63.0	100.0
32	80	2.95	4.83	7.57	11.35	19.57	27.20	27.72	29.90	32.03	34.10	37.03	38.83	41.8	134.9	214.0
40	80	4.49	7.38	11.55	17.29	29.81	41.42	42.22	45.54	48.78	51.94	56.40	59.14	57.5	205.7	326.5
50	40	10.47	17.16	26.81	40.20	69.20	96.18	98.04	105.75	113.27	120.59	130.96	137.33	109.2	477.6	758.2
65	40	16.68	27.33	42.72	63.93	110.18	152.98	155.95	168.20	180.17	191.81	208.31	218.44	155.7	761.1	1205.9
80	40	29.51	48.38	75.47	112.96	194.49	270.35	275.59	297.25	318.40	338.98	368.13	386.03	240.5	1344.9	2131.2
100	40	60.26	98.60	153.84	230.29	396.56	550.03	560.67	604.72	647.76	689.61	748.91	785.34	414.3	2735.7	4335.6
125	40	108.75	177.97	277.71	415.78	714.27	991.91	1012.44	1091.99	1169.71	1245.28	1352.37	1418.15	650.6	4939.2	7819.0
150	40	176.25	287.77	449.08	671.57	1155.17	1604.32	1635.36	1763.85	1889.38	2011.45	2184.43	2290.69	940.3	7988.0	12 629.7
200	40	360.41	589.35	918.60	1373.79	2363.28	3277.89	3341.30	3603.84	3860.32	4109.73	4463.15	4680.25	1628.2	16 342.0	25 838.1
250	40	652.69	1065.97	1661.62	2485.16	4275.41	5930.04	6044.77	6519.73	6983.73	7434.94	8074.30	8467.06	2566.4	29 521.7	46 743.9
300	ID[b]	1044.01	1705.26	2658.28	3970.05	6830.36	9488.03	9671.59	10 431.52	11 173.92	11 895.85	12 918.83	13 547.24	3680.9	47 161.0	74 677.7
350	30	1351.59	2207.80	3436.53	5140.20	8843.83	12 266.49	12 503.79	13 486.26	14 446.06	15 379.40	16 701.95	17 514.38	4487.7	61 061.2	96 691.3
400	30	1947.52	3176.58	4959.92	7407.49	12 725.25	17 677.86	18 019.86	19 435.74	20 818.96	22 164.04	24 070.04	25 240.87	5944.7	87 994.9	139 346.8

Table 8.18 Suction, Discharge, and Liquid Line Capacities in Kilowatts for Refrigerant 507A (Single- or High-Stage Applications)

[2014R, Ch 1. Tbl 7]

Line Size	Suction Lines ($\Delta t = 0.04$ K/m)						Discharge Lines ($\Delta t = 0.02$ K/m, $\Delta p = 74.90$)						Liquid Lines (40°C)		
Type L Copper, OD, mm	Saturated Suction Temperature, °C						Saturated Suction Temperature, °C						See note a		
	−50	−40	−30	−20	−5	5	−50	−40	−30	−20	−5	5	Velocity = 0.5 m/s	$\Delta t =$ 0.02 K/m Drop	$\Delta t =$ 0.05 K/m Drop
	Corresponding Δp, Pa/m						Corresponding Δp, Pa/m								
	173.7	251.7	350.3	471.6	700.5	882.5	896.3	896.3	896.3	896.3	896.3	896.3		$\Delta p = 896.3$	$\Delta p = 2240.8$
12	0.16	0.28	0.44	0.68	1.21	1.70	1.72	1.86	2.00	2.13	2.32	2.43	4.0	7.9	13.0
15	0.31	0.53	0.85	1.30	2.31	3.24	3.27	3.54	3.80	4.05	4.41	4.63	6.5	15.0	24.7
18	0.55	0.92	1.47	2.26	4.00	5.61	5.66	6.12	6.57	7.01	7.63	8.01	9.8	26.1	42.8
22	0.97	1.63	2.60	3.98	7.02	9.85	9.93	10.73	11.52	12.29	13.37	14.04	15.0	45.9	75.1
28	1.91	3.22	5.14	7.85	13.83	19.38	19.53	21.12	22.67	24.18	26.31	27.63	25.1	90.5	147.8
35	3.52	5.91	9.42	14.37	25.28	35.40	35.68	38.58	41.42	44.17	48.07	50.47	39.7	165.6	270.0
42	5.86	9.82	15.65	23.83	41.86	58.55	59.03	63.82	68.52	73.07	79.52	83.50	58.2	274.8	447.1
54	11.68	19.55	31.07	47.24	82.83	115.76	116.74	126.22	135.51	144.51	157.26	165.12	98.0	544.0	883.9
67	20.86	34.83	55.25	84.08	147.12	205.36	206.75	223.53	239.99	255.92	278.52	292.43	151.9	967.0	1567.7
79	32.31	54.01	85.61	129.94	227.12	317.17	319.34	345.26	370.68	395.29	430.19	451.67	211.9	1497.3	2420.9
105	69.31	115.54	182.78	277.24	484.29	675.47	678.77	733.87	787.90	840.21	914.39	960.06	378.2	3189.5	5154.4
130	123.41	205.61	325.01	492.45	857.55	1194.03	1202.46	1300.07	1395.78	1488.45	1619.87	1700.76	586.7	5666.6	9129.4
156	200.86	333.77	526.96	797.36	1389.26	1935.01	1946.66	2104.68	2259.62	2409.65	2622.39	2753.36	849.9	9175.8	14 793.3
206	412.07	683.01	1078.30	1631.18	2832.25	3937.64	3966.22	4288.18	4603.88	4909.55	5343.00	5609.84	1470.7	18 734.6	30 099.9
257	733.42	1216.78	1916.48	2891.11	5022.65	6984.91	7027.87	7598.35	8157.74	8699.37	9467.42	9940.23	2286.7	33 285.5	53 389.2

Table 8.18 Suction, Discharge, and Liquid Line Capacities in Kilowatts for Refrigerant 507A (Single- or High-Stage Applications) [2014R, Ch 1. Tbl 7] ***(Continued)***

Line Size		Suction Lines (Δt = 0.04 K/m)						Discharge Lines (Δt = 0.02 K/m, Δp = 74.90)						Liquid Lines (40°C)		
		Saturated Suction Temperature, °C						Saturated Suction Temperature, °C						See note a		
		–50	–40	–30	–20	–5	5	–50	–40	–30	–20	–5	5	Velocity = 0.5 m/s	Δt = 0.02 K/m Drop	Δt = 0.05 K/m Drop
		Corresponding Δp, Pa/m						Corresponding Δp, Pa/m								
		173.7	251.7	350.3	471.6	700.5	882.5	896.3	896.3	896.3	896.3	896.3	896.3		Δp = 896.3	Δp = 2240.8
Steel																
mm	SCH															
10	80	0.16	0.26	0.41	0.62	1.06	1.47	1.48	1.60	1.72	1.83	1.99	2.09	4.4	7.1	11.3
15	80	0.31	0.52	0.81	1.21	2.09	2.90	2.91	3.15	3.38	3.60	3.92	4.12	7.4	13.9	22.2
20	80	0.71	1.17	1.83	2.74	4.71	6.52	6.55	7.09	7.61	8.11	8.83	9.27	13.6	31.4	49.9
25	80	1.40	2.29	3.58	5.36	9.23	12.77	12.83	13.87	14.89	15.88	17.28	18.15	22.6	61.6	97.7
32	80	3.01	4.93	7.68	11.50	19.76	27.33	27.47	29.70	31.88	34.00	37.00	38.85	40.3	132.0	209.4
40	80	4.59	7.52	11.72	17.54	30.09	41.63	41.83	45.23	48.56	51.78	56.35	59.17	55.6	201.0	319.0
50	40	10.69	17.50	27.25	40.71	69.87	96.67	97.14	105.02	112.76	120.24	130.86	137.39	105.5	466.6	740.7
65	40	17.06	27.88	43.32	64.81	111.37	153.76	154.51	167.05	179.35	191.26	208.14	218.54	150.4	743.5	1178.1
80	40	30.20	49.26	76.63	114.52	196.37	271.72	273.05	295.22	316.95	338.00	367.84	386.21	232.3	1313.9	2082.0
100	40	61.60	100.39	156.20	233.20	400.40	552.81	555.50	600.59	644.81	687.62	748.33	785.70	400.3	2675.6	4235.5
125	40	111.17	181.20	281.64	421.03	721.18	998.16	1003.06	1084.49	1164.33	1241.63	1351.25	1418.74	628.6	4825.1	7638.5
150	40	179.98	292.99	455.44	680.92	1166.35	1612.43	1620.28	1751.80	1880.77	2005.64	2182.72	2291.73	908.5	7803.5	12 338.1
200	40	368.55	600.02	931.61	1393.04	2386.16	3294.46	3310.49	3579.22	3842.72	4097.86	4459.65	4682.37	1573.2	15 964.7	25 241.5
250	40	666.52	1085.29	1685.18	2516.51	4316.82	5960.02	5989.03	6475.19	6951.89	7413.46	8067.98	8470.90	2479.7	28 840.0	45 664.6
300	ID[b]	1067.53	1736.16	2695.93	4020.13	6896.51	9535.99	9582.41	10 360.26	11 122.98	11 861.49	12 908.71	13 553.39	3556.5	46 140.3	72 953.4
350	30	1380.23	2247.80	3485.20	5205.04	8929.47	12 328.49	12 388.50	13 394.13	14 380.20	15 334.97	16 688.86	17 522.33	4336.1	59 651.3	94 458.7
400	30	1991.54	3239.15	5030.17	7500.91	12 848.49	17 767.21	17 853.70	19 302.97	20 724.05	22 100.02	24 051.18	25 252.33	5743.9	85 963.1	136 129.3

Table 8.19 Suction, Discharge, and Liquid Line Capacities in Kilowatts for Refrigerant 410A (Single- or High-Stage Applications)

[2014R, Ch 1, Tbl 8]

Line Size	Suction Lines (Δt = 0.04 K/m)						Discharge Lines (Δt = 0.02 K/m, Δp = 74.90)						Liquid Lines (40°C)		
	Saturated Suction Temperature, °C						Saturated Suction Temperature, °C						See note a		
Type L Copper, OD, mm	–50	–40	–30	–20	–5	5	–50	–40	–30	–20	–5	5	Velocity = 0.5 m/s	Δt = 0.02 K/m Drop	Δt = 0.05 K/m Drop
	Corresponding Δp, Pa/m						Corresponding Δp, Pa/m								
	218.6	317.2	443.3	599.1	894.2	1137.6	1172.1	1172.1	1172.1	1172.1	1172.1	1172.1		Δp = 1179	Δp = 2935.8
12	0.32	0.52	0.80	1.20	2.05	2.83	3.47	3.60	3.73	3.84	4.00	4.07	6.2	14.3	23.5
15	0.61	0.99	1.54	2.29	3.90	5.37	6.60	6.85	7.09	7.31	7.60	7.75	10.1	27.2	44.6
18	1.06	1.72	2.68	3.98	6.76	9.30	11.43	11.87	12.29	12.67	13.16	13.42	15.4	47.3	77.2
22	1.87	3.04	4.72	7.00	11.89	16.32	20.04	20.81	21.54	22.20	23.08	23.53	23.5	83.0	135.3
28	3.72	6.03	9.32	13.82	23.43	32.11	39.44	40.95	42.39	43.70	45.42	46.31	39.3	163.7	266.4
35	6.84	11.07	17.11	25.33	42.82	58.75	72.05	74.82	77.46	79.84	82.98	84.62	62.2	299.6	486.0
42	11.39	18.39	28.38	42.00	70.89	97.02	119.01	123.57	127.93	131.87	137.06	139.76	91.3	495.7	804.1
54	22.70	36.61	56.35	83.26	140.29	191.84	235.35	244.38	253.00	260.80	271.06	276.39	153.7	982.0	1590.3
67	40.48	65.21	100.35	147.94	249.16	340.33	417.58	433.60	448.89	462.73	480.93	490.40	238.2	1746.4	2816.7
79	62.89	101.10	155.22	229.02	384.65	525.59	643.78	668.47	692.05	713.37	741.44	756.03	332.2	2695.2	4350.8
105	134.69	216.27	331.96	488.64	820.20	1119.32	1371.21	1423.81	1474.02	1519.45	1579.22	1610.30	592.9	5744.4	9249.0
130	240.18	384.82	590.29	866.21	1452.34	1978.69	2424.14	2517.13	2605.89	2686.20	2791.88	2846.83	919.8	10 188.7	16 386.3
156	390.21	625.92	957.07	1405.29	2352.81	3206.57	3928.86	4079.57	4223.44	4353.60	4524.87	4613.92	1332.3	16 502.3	26 500.6
206	800.39	1280.57	1956.28	2868.65	4796.70	6532.82	7995.81	8302.53	8595.32	8860.22	9208.77	9390.02	2305.4	33 708.0	53 996.3
257	1427.49	2276.75	3480.75	5095.42	8506.22	11 575.35	14 185.59	14 729.76	15 249.20	15 719.17	16 337.55	16 659.10	3584.6	59 763.6	95 683.0

Table 8.19 Suction, Discharge, and Liquid Line Capacities in Kilowatts for Refrigerant 410A (Single- or High-Stage Applications) [2014R, Ch 1, Tbl 8] ***(Continued)***

Line Size		Suction Lines (Δt = 0.04 K/m)						Discharge Lines (Δt = 0.02 K/m, Δp = 74.90)						Liquid Lines (40°C)		
		Saturated Suction Temperature, °C						Saturated Suction Temperature, °C						See note a		
		–50	–40	–30	–20	–5	5	–50	–40	–30	–20	–5	5	Velocity = 0.5 m/s	Δt = 0.02 K/m Drop	Δt = 0.05 K/m Drop
		Corresponding Δp, Pa/m						Corresponding Δp, Pa/m								
		218.6	317.2	443.3	599.1	894.2	1137.6	1172.1	1172.1	1172.1	1172.1	1172.1	1172.1		Δp = 1179	Δp = 2935.8
Steel																
mm	SCH															
10	80	0.31	0.49	0.74	1.08	1.80	2.44	2.98	3.10	3.21	3.31	3.44	3.50	6.9	12.7	20.1
15	80	0.61	0.97	1.47	2.14	3.54	4.80	5.87	6.09	6.31	6.50	6.76	6.89	11.5	25.0	39.6
20	80	1.39	2.19	3.32	4.82	7.98	10.81	13.21	13.72	14.20	14.64	15.22	15.52	21.3	56.2	89.1
25	80	2.72	4.30	6.50	9.45	15.63	21.16	25.86	26.85	27.80	28.66	29.79	30.37	35.5	110.2	174.5
32	80	5.86	9.24	13.95	20.26	33.47	45.30	55.37	57.50	59.53	61.36	63.77	65.03	63.2	235.9	
40	80	8.94	14.09	21.28	30.91	50.97	68.99	84.33	87.57	90.66	93.45	97.13	99.04	87.1	359.8	568.9
50	40	20.81	32.75	49.39	71.75	118.34	160.19	195.83	203.34	210.51	217.00	225.54	229.98	165.4	835.4	1320.9
65	40	33.22	52.18	78.69	114.11	188.61	254.80	311.49	323.43	334.84	345.16	358.74	365.80	235.8	1328.6	2101.0
80	40	58.79	92.36	139.17	201.84	332.58	450.29	550.47	571.59	591.74	609.98	633.98	646.46	364.2	2347.8	3713.1
100	40	119.78	188.24	283.69	411.01	678.11	916.08	1121.21	1164.22	1205.28	1242.42	1291.30	1316.72	627.6	4787.0	7562.8
125	40	216.38	339.76	511.52	742.06	1221.40	1654.16	2022.16	2099.73	2173.77	2240.77	2328.92	2374.75	985.4	8622.2	13 639.9
150	40	350.32	549.37	827.18	1200.12	1975.34	2672.01	3266.45	3391.75	3511.36	3619.58	3761.97	3836.01	1424.2	13 944.5	22 032.9
200	40	717.23	1125.10	1692.00	2451.89	4041.21	5459.36	6673.89	6929.91	7174.29	7395.39	7686.32	7837.60	2466.2	28 528.0	45 016.9
250	40	1297.30	2035.01	3060.66	4435.35	7310.97	9876.55	12 073.76	12 536.92	12 979.03	13 379.03	13 905.35	14 179.04	3887.3	51 535.6	81 440.3
300	ID[b]	2075.09	3255.45	4896.39	7085.49	11 679.95	15 802.42	19 317.94	20 059.00	20 766.37	21 406.37	22 248.47	22 686.37	5575.3	82 451.9	130 304.0
350	30	2686.45	4214.83	6329.87	9173.88	15 122.98	20 429.97	24 974.96	25 933.02	26 847.53	27 674.95	28 763.66	29 329.79	6797.4	106 757.2	168 461.9
400	30	3870.92	6064.31	9135.88	13 220.36	21 760.24	29 442.67	35 992.70	37 373.41	38 691.36	39 883.80	41 452.79	42 268.67	9004.3	153 611.4	242 779.1

Table 8.20 Suction, Discharge, and Liquid Line Capacities in Kilowatts for Refrigerant 407C (Single- or High-Stage Applications)
[2014R, Ch 1, Tbl 9]

Line Size	Suction Lines (Δt = 0.04 K/m)						Discharge Lines (Δt = 0.02 K/m, Δp = 74.90)						Liquid Lines (40°C)		
Type L Copper, OD, mm	Saturated Suction Temperature, °C						Saturated Suction Temperature, °C						See note a		
	–50	–40	–30	–20	–5	5	–50	–40	–30	–20	–5	5	Velocity = 0.5 m/s	Δt = 0.02 K/m Drop	Δt = 0.05 K/m Drop
	Corresponding Δp, Pa/m						Corresponding Δp, Pa/m								
	173.7	251.7	350.3	471.6	700.5	882.5	896.3	896.3	896.3	896.3	896.3	896.3		Δp = 896.3	Δp = 2240.8
12	0.16	0.28	0.44	0.68	1.21	1.70	1.72	1.86	2.00	2.13	2.32	2.43	4.0	7.9	13.0
15	0.31	0.53	0.85	1.30	2.31	3.24	3.27	3.54	3.80	4.05	4.41	4.63	6.5	15.0	24.7
18	0.55	0.92	1.47	2.26	4.00	5.61	5.66	6.12	6.57	7.01	7.63	8.01	9.8	26.1	42.8
22	0.97	1.63	2.60	3.98	7.02	9.85	9.93	10.73	11.52	12.29	13.37	14.04	15.0	45.9	75.1
28	1.91	3.22	5.14	7.85	13.83	19.38	19.53	21.12	22.67	24.18	26.31	27.63	25.1	90.5	147.8
35	3.52	5.91	9.42	14.37	25.28	35.40	35.68	38.58	41.42	44.17	48.07	50.47	39.7	165.6	270.0
42	5.86	9.82	15.65	23.83	41.86	58.55	59.03	63.82	68.52	73.07	79.52	83.50	58.2	274.8	447.1
54	11.68	19.55	31.07	47.24	82.83	115.76	116.74	126.22	135.51	144.51	157.26	165.12	98.0	544.0	883.9
67	20.86	34.83	55.25	84.08	147.12	205.36	206.75	223.53	239.99	255.92	278.52	292.43	151.9	967.0	1567.7
79	32.31	54.01	85.61	129.94	227.12	317.17	319.34	345.26	370.68	395.29	430.19	451.67	211.9	1497.3	2420.9
105	69.31	115.54	182.78	277.24	484.29	675.47	678.77	733.87	787.90	840.21	914.39	960.06	378.2	3189.5	5154.4
130	123.41	205.61	325.01	492.45	857.55	1194.03	1202.46	1300.07	1395.78	1488.45	1619.87	1700.76	586.7	5666.6	9129.4
156	200.86	333.77	526.96	797.36	1389.26	1935.01	1946.66	2104.68	2259.62	2409.65	2622.39	2753.36	849.9	9175.8	14 793.3
206	412.07	683.01	1078.30	1631.18	2832.25	3937.64	3966.22	4288.18	4603.88	4909.55	5343.00	5609.84	1470.7	18 734.6	30 099.9
257	733.42	1216.78	1916.48	2891.11	5022.65	6984.91	7027.87	7598.35	8157.74	8699.37	9467.42	9940.23	2286.7	33 285.5	53 389.2

Table 8.20 Suction, Discharge, and Liquid Line Capacities in Kilowatts for Refrigerant 407C (Single- or High-Stage Applications) [2014R, Ch 1, Tbl 9] ***(Continued)***

Line Size		Suction Lines (Δt = 0.04 K/m)						Discharge Lines (Δt = 0.02 K/m, Δp = 74.90)						Liquid Lines (40°C)		
		Saturated Suction Temperature, °C						Saturated Suction Temperature, °C						See note a		
		–50	–40	–30	–20	–5	5	–50	–40	–30	–20	–5	5	Velocity = 0.5 m/s	Δt = 0.02 K/m Drop	Δt = 0.05 K/m Drop
		Corresponding Δp, Pa/m						Corresponding Δp, Pa/m								
		173.7	251.7	350.3	471.6	700.5	882.5	896.3	896.3	896.3	896.3	896.3	896.3		Δp = 896.3	Δp = 2240.8
Steel																
mm	SCH															
10	80	0.16	0.26	0.41	0.62	1.06	1.47	1.48	1.60	1.72	1.83	1.99	2.09	4.4	7.1	11.3
15	80	0.31	0.52	0.81	1.21	2.09	2.90	2.91	3.15	3.38	3.60	3.92	4.12	7.4	13.9	22.2
20	80	0.71	1.17	1.83	2.74	4.71	6.52	6.55	7.09	7.61	8.11	8.83	9.27	13.6	31.4	49.9
25	80	1.40	2.29	3.58	5.36	9.23	12.77	12.83	13.87	14.89	15.88	17.28	18.15	22.6	61.6	97.7
32	80	3.01	4.93	7.68	11.50	19.76	27.33	27.47	29.70	31.88	34.00	37.00	38.85	40.3	132.0	209.4
40	80	4.59	7.52	11.72	17.54	30.09	41.63	41.83	45.23	48.56	51.78	56.35	59.17	55.6	201.0	319.0
50	40	10.69	17.50	27.25	40.71	69.87	96.67	97.14	105.02	112.76	120.24	130.86	137.39	105.5	466.6	740.7
65	40	17.06	27.88	43.32	64.81	111.37	153.76	154.51	167.05	179.35	191.26	208.14	218.54	150.4	743.5	1178.1
80	40	30.20	49.26	76.63	114.52	196.37	271.72	273.05	295.22	316.95	338.00	367.84	386.21	232.3	1313.9	2082.0
100	40	61.60	100.39	156.20	233.20	400.40	552.81	555.50	600.59	644.81	687.62	748.33	785.70	400.3	2675.6	4235.5
125	40	111.17	181.20	281.64	421.03	721.18	998.16	1003.06	1084.49	1164.33	1241.63	1351.25	1418.74	628.6	4825.1	7638.5
150	40	179.98	292.99	455.44	680.92	1166.35	1612.43	1620.28	1751.80	1880.77	2005.64	2182.72	2291.73	908.5	7803.5	12 338.1
200	40	368.55	600.02	931.61	1393.04	2386.16	3294.46	3310.49	3579.22	3842.72	4097.86	4459.65	4682.37	1573.2	15 964.7	25 241.5
250	40	666.52	1085.29	1685.18	2516.51	4316.82	5960.02	5989.03	6475.19	6951.89	7413.46	8067.98	8470.90	2479.7	28 840.0	45 664.6
300	ID[b]	1067.53	1736.16	2695.93	4020.13	6896.51	9535.99	9582.41	10 360.26	11 122.98	11 861.49	12 908.71	13 553.39	3556.5	46 140.3	72 953.4
350	30	1380.23	2247.80	3485.20	5205.04	8929.47	12 328.49	12 388.50	13 394.13	14 380.20	15 334.97	16 688.86	17 522.33	4336.1	59 651.3	94 458.7
400	30	1991.54	3239.15	5030.17	7500.91	12 848.49	17 767.21	17 853.70	19 302.97	20 724.05	22 100.02	24 051.18	25 252.33	5743.9	85 963.1	136 129.3

Table 8.21 Suction, Discharge, and Liquid Line Capacities in Kilowatts for Refrigerant 22 (Single- or High-Stage Applications)
[2014R, Ch 1, Tbl 3]

Nominal Line OD, mm	Suction Lines ($\Delta t = 0.04$ K/m)					Discharge Lines ($\Delta t = 0.02$ K/m, $\Delta p = 74.90$)			Liquid Lines	
	Saturated Suction Temperature, °C					Saturated Suction Temperature, °C			See note a	
	–40	–30	–20	–5	5					
	Corresponding Δp, Pa/m								Velocity = 0.5 m/s	$\Delta t =$ 0.02 K/m $\Delta p = 749$
	196	277	378	572	731	–40	–20	5		
TYPE L COPPER LINE										
12	0.32	0.50	0.75	1.28	1.76	2.30	2.44	2.60	7.08	11.24
15	0.61	0.95	1.43	2.45	3.37	4.37	4.65	4.95	11.49	21.54
18	1.06	1.66	2.49	4.26	5.85	7.59	8.06	8.59	17.41	37.49
22	1.88	2.93	4.39	7.51	10.31	13.32	14.15	15.07	26.66	66.18
28	3.73	5.82	8.71	14.83	20.34	26.24	27.89	29.70	44.57	131.0
35	6.87	10.70	15.99	27.22	37.31	48.03	51.05	54.37	70.52	240.7
42	11.44	17.80	26.56	45.17	61.84	79.50	84.52	90.00	103.4	399.3
54	22.81	35.49	52.81	89.69	122.7	157.3	167.2	178.1	174.1	794.2
67	40.81	63.34	94.08	159.5	218.3	279.4	297.0	316.3	269.9	1415.0
79	63.34	98.13	145.9	247.2	337.9	431.3	458.5	488.2	376.5	2190.9
105	136.0	210.3	312.2	527.8	721.9	919.7	977.6	1041.0	672.0	4697.0
STEEL LINE										
10	0.47	0.72	1.06	1.78	2.42	3.04	3.23	3.44	10.66	15.96
15	0.88	1.35	1.98	3.30	4.48	5.62	5.97	6.36	16.98	29.62
20	1.86	2.84	4.17	6.95	9.44	11.80	12.55	13.36	29.79	62.55
25	3.52	5.37	7.87	13.11	17.82	22.29	23.70	25.24	48.19	118.2
32	7.31	11.12	16.27	27.11	36.79	46.04	48.94	52.11	83.56	244.4
40	10.98	16.71	24.45	40.67	55.21	68.96	73.31	78.07	113.7	366.6

Table 8.21 Suction, Discharge, and Liquid Line Capacities in Kilowatts for Refrigerant 22 (Single- or High-Stage Applications) [2014R, Ch 1, Tbl 3] ***(Continued)***

Nominal Line OD, mm	Suction Lines ($\Delta t = 0.04$ K/m) Saturated Suction Temperature, °C					Discharge Lines ($\Delta t = 0.02$ K/m, $\Delta p = 74.90$) Saturated Suction Temperature, °C			Liquid Lines See note a	
	–40	–30	–20	–5	5				Velocity = 0.5 m/s	$\Delta t =$ 0.02 K/m $\Delta p = 749$
	Corresponding Δp, Pa/m									
	196	277	378	572	731	–40	–20	5		
STEEL LINE *(Continued)*										
50	21.21	32.23	47.19	78.51	106.4	132.9	141.3	150.5	187.5	707.5
65	33.84	51.44	75.19	124.8	169.5	211.4	224.7	239.3	267.3	1127.3
80	59.88	90.95	132.8	220.8	299.5	373.6	397.1	422.9	412.7	1991.3
100	122.3	185.6	270.7	450.1	610.6	761.7	809.7	862.2	711.2	4063.2

Notes:

1. Table capacities are in kilowatts of refrigeration.

   Δp = pressure drop per unit equivalent length of line, Pa/m

   Δt = corresponding change in saturation temperature, K/m

2. Line capacity for other saturation temperatures Δt and equivalent lengths L_e

$$\text{Line capacity} = \text{Table capacity}\left(\frac{\text{Table } L_e}{\text{Actual } L_e} \times \frac{\text{Actual } \Delta t}{\text{Table } \Delta t}\right)^{0.55}$$

3. Saturation temperature Δt for other capacities and equivalent lengths L_e

$$\Delta t = \text{Table } \Delta t\left(\frac{\text{Actual } L_e}{\text{Table } L_e}\right)\left(\frac{\text{Actual capacity}}{\text{Table capacity}}\right)^{1.8}$$

4. Values based on 40°C condensing temperature. Multiply table capacities by the following factors for other condensing temperatures.

Condensing Temperature, °C	Suction Line	Discharge Line
20	1.18	0.80
30	1.10	0.88
40	1.00	1.00
50	0.91	1.11

[a] Sizing is recommended where any gas generated in receiver must return up condensate line to condenser without restricting condensate flow. Water-cooled condensers, where receiver ambient temperature may be higher than refrigerant condensing temperature, fall into this category.

[b] Line pressure drop Δp is conservative; if subcooling is substantial or line is short, a smaller size line may be used. Applications with very little subcooling or very long lines may require a larger line.

Table 8.22 Suction, Discharge, and Liquid Line Capacities in Kilowatts for Refrigerant 134a (Single- or High-Stage Applications
[2014R, Ch 1, Tbl 5]

Nominal Line OD, mm	Suction Lines ($\Delta t = 0.04$ K/m)					Discharge Lines ($\Delta t = 0.02$ K/m, $\Delta p = 538$ Pa/m)			Liquid Lines	
	Saturated Suction Temperature, °C					Saturated Suction Temperature, °C			See note a	
	–10	–5	0	5	10					
	Corresponding Δp, Pa/m									
	318	368	425	487	555	–10	0	10	Velocity = 0.5 m/s	$\Delta t = 0.02$ K/m $\Delta p = 538$ Pa/m
TYPE L COPPER LINE										
12	0.62	0.76	0.92	1.11	1.33	1.69	1.77	1.84	6.51	8.50
15	1.18	1.45	1.76	2.12	2.54	3.23	3.37	3.51	10.60	16.30
18	2.06	2.52	3.60	3.69	4.42	5.61	5.85	6.09	16.00	28.40
22	3.64	4.45	5.40	6.50	7.77	9.87	10.30	10.70	24.50	50.10
28	7.19	8.80	10.70	12.80	15.30	19.50	20.30	21.10	41.00	99.50
35	13.20	16.10	19.50	23.50	28.10	35.60	37.20	38.70	64.90	183.00
42	21.90	26.80	32.40	39.00	46.50	59.00	61.60	64.10	95.20	304.00
54	43.60	53.20	64.40	77.30	92.20	117.00	122.00	127.00	160.00	605.00
67	77.70	94.60	115.00	138.00	164.00	208.00	217.00	226.00	248.00	1080.00
79	120.00	147.00	177.00	213.00	253.00	321.00	335.00	349.00	346.00	1670.00
105	257.00	313.00	379.00	454.00	541.00	686.00	715.00	744.00	618.00	3580.00
STEEL LINE										
10	0.87	1.06	1.27	1.52	1.80	2.28	2.38	2.47	9.81	12.30
15	1.62	1.96	2.36	2.81	3.34	4.22	4.40	4.58	15.60	22.80
20	3.41	4.13	4.97	5.93	7.02	8.88	9.26	9.64	27.40	48.20
25	6.45	7.81	9.37	11.20	13.30	16.70	17.50	18.20	44.40	91.00
32	13.30	16.10	19.40	23.10	27.40	34.60	36.10	37.50	76.90	188.00
40	20.00	24.20	29.10	34.60	41.00	51.90	54.10	56.30	105.00	283.00

Table 8.22 Suction, Discharge, and Liquid Line Capacities in Kilowatts for Refrigerant 134a (Single- or High-Stage Applications [2014R, Ch 1, Tbl 5] ***(Continued)***

Nominal Line OD, mm	Suction Lines ($\Delta t = 0.04$ K/m) Saturated Suction Temperature, °C					Discharge Lines ($\Delta t = 0.02$ K/m, $\Delta p = 538$ Pa/m) Saturated Suction Temperature, °C			Liquid Lines See note a	
	–10	–5	0	5	10				Velocity = 0.5 m/s	$\Delta t = 0.02$ K/m $\Delta p = 538$ Pa/m
	Corresponding Δp, Pa/m									
	318	368	425	487	555	–10	0	10		
STEEL LINE *(Continued)*										
50	38.60	46.70	56.00	66.80	79.10	100.00	104.00	108.00	173.00	546.00
65	61.50	74.30	89.30	106.00	126.00	159.00	166.00	173.00	246.00	871.00
80	109.00	131.00	158.00	288.00	223.00	281.00	294.00	306.00	380.00	1540.00
100	222.00	268.00	322.00	383.00	454.00	573.00	598.00	622.00	655.00	3140.00

Notes:

1. Table capacities are in kilowatts of refrigeration.

Δp = pressure drop per equivalent line length, Pa/m

Δt = corresponding change in saturation temperature, K/m

2. Line capacity for other saturation temperatures Δt and equivalent lengths L_e

$$\text{Line capacity} = \text{Table capacity}\left(\frac{\text{Table } L_e}{\text{Actual } L_e} \times \frac{\text{Actual } \Delta t}{\text{Table } \Delta t}\right)^{0.55}$$

3. Saturation temperature Δt for other capacities and equivalent lengths L_e

$$\Delta t = \text{Table } \Delta t \left(\frac{\text{Actual } L_e}{\text{Table } L_e}\right)\left(\frac{\text{Actual capacity}}{\text{Table capacity}}\right)^{1.8}$$

4. Values based on 40°C condensing temperature. Multiply table capacities by the following factors for other condensing temperatures.

Condensing Temperature, °C	Suction Line	Discharge Line
20	1.239	0.682
30	1.120	0.856
40	1.0	1.0
50	0.888	1.110

[a] Sizing is recommended where any gas generated in receiver must return up condensate line to condenser without restricting condensate flow. Water-cooled condensers, where receiver ambient temperature may be higher than refrigerant condensing temperature, fall into this category.

[b] Line pressure drop Δp is conservative; if subcooling is substantial or line is short, a smaller size line may be used. Applications with very little subcooling or very long lines may require a larger line.

Table 8.23 Minimum Refrigeration Capacity in Kilowatts for Oil Entrainment up Suction Risers (Copper Tubing, ASTM B 88M Type B, Metric Size)
[2014R, Ch 1, Tbl 19]

Refrigerant	Saturated Temp., °C	Suction Gas Temp., °C	Tubing Nominal OD, mm											
			12	15	18	22	28	35	42	54	67	79	105	130
22	–40	–35	0.182	0.334	0.561	0.956	1.817	3.223	5.203	9.977	14.258	26.155	53.963	93.419
		–25	0.173	0.317	0.532	0.907	1.723	3.057	4.936	9.464	16.371	24.811	51.189	88.617
		–15	0.168	0.307	0.516	0.880	1.672	2.967	4.791	9.185	15.888	24.080	49.681	86.006
	–20	–15	0.287	0.527	0.885	1.508	2.867	5.087	8.213	15.748	27.239	41.283	85.173	147.449
		–5	0.273	0.501	0.841	1.433	2.724	4.834	7.804	14.963	25.882	39.226	80.929	140.102
		5	0.264	0.485	0.815	1.388	2.638	4.680	7.555	14.487	25.058	37.977	78.353	135.642
	–5	0	0.389	0.713	1.198	2.041	3.879	6.883	11.112	21.306	36.854	55.856	115.240	199.499
		10	0.369	0.676	1.136	1.935	3.678	6.526	10.535	20.200	34.940	52.954	109.254	189.136
		20	0.354	0.650	1.092	1.861	3.537	6.275	10.131	19.425	33.600	50.924	105.065	181.884
	5	10	0.470	0.862	1.449	2.468	4.692	8.325	13.441	25.771	44.577	67.560	139.387	241.302
		20	0.440	0.807	1.356	2.311	4.393	7.794	12.582	24.126	41.731	63.246	130.488	225.896
		30	0.422	0.774	1.301	2.217	4.213	7.476	12.069	23.141	40.027	60.665	125.161	216.675

Table 8.23 Minimum Refrigeration Capacity in Kilowatts for Oil Entrainment up Suction Risers (Copper Tubing, ASTM B 88M Type B, Metric Size) [2014R, Ch 1, Tbl 19] ***(Continued)***

Refrigerant	Saturated Temp., °C	Suction Gas Temp., °C	Tubing Nominal OD, mm											
			12	15	18	22	28	35	42	54	67	79	105	130
134a	–10	–5	0.274	0.502	0.844	1.437	2.732	4.848	7.826	15.006	25.957	39.340	81.164	140.509
		5	0.245	0.450	0.756	1.287	2.447	4.342	7.010	13.440	23.248	35.235	72.695	125.847
		15	0.238	0.436	0.732	1.247	2.370	4.206	6.790	13.019	22.519	34.129	70.414	121.898
	–5	0	0.296	0.543	0.913	1.555	2.956	5.244	8.467	16.234	28.081	42.559	87.806	152.006
		10	0.273	0.500	0.840	1.431	2.720	4.827	7.792	14.941	25.843	39.168	80.809	139.894
		20	0.264	0.484	0.813	1.386	2.634	4.674	7.546	14.468	25.026	37.929	78.254	135.471
	5	10	0.357	0.655	1.100	1.874	3.562	6.321	10.204	19.565	33.843	51.292	105.823	183.197
		20	0.335	0.615	1.033	1.761	3.347	5.938	9.586	18.380	31.792	48.184	99.412	172.098
		30	0.317	0.582	0.978	1.667	3.168	5.621	9.075	17.401	30.099	45.617	94.115	162.929
	10	15	0.393	0.721	1.211	2.063	3.921	6.957	11.232	21.535	37.250	56.456	116.479	201.643
		25	0.370	0.679	1.141	1.944	3.695	6.555	10.583	20.291	35.098	53.195	109.749	189.993
		35	0.358	0.657	1.104	1.881	3.576	6.345	10.243	19.640	33.971	51.486	106.224	183.891

Notes:

1. Refrigeration capacity in kilowatts is based on saturated evaporator as shown in table and condensing temperature of 40°C. For other liquid line temperatures, use correction factors in table at right.
2. Values computed using ISO 32 mineral oil for R-22 and R-502. R-134a computed using ISO 32 ester-based oil.

Refrigerant	Liquid Temperature, °C		
	20	30	50
22	1.17	1.08	0.91
134a	1.20	1.10	0.89

Table 8.24 Minimum Refrigeration Capacity in Kilowatts for Oil Entrainment up Hot-Gas Risers (Copper Tubing, ASTM B 88M Type B, Metric Size) [2014R, Ch 1, Tbl 20]

Refrigerant	Saturated Discharge Temp., °C	Discharge Gas Temp., °C	Tubing Diameter, Nominal OD, mm											
			12	15	18	22	28	35	42	54	67	79	105	130
22	20	60	0.563	0.032	0.735	2.956	5.619	9.969	16.094	30.859	43.377	80.897	116.904	288.938
		70	0.549	1.006	1.691	2.881	5.477	9.717	15.687	30.078	52.027	48.851	162.682	281.630
		80	0.535	0.982	1.650	2.811	5.343	9.480	15.305	29.346	50.761	76.933	158.726	173.780
	30	70	0.596	1.092	1.836	3.127	5.945	10.547	17.028	32.649	56.474	85.591	176.588	305.702
		80	0.579	1.062	1.785	3.040	5.779	10.254	16.554	31.740	54.901	83.208	171.671	297.190
		90	0.565	0.035	1.740	2.964	5.635	9.998	16.140	30.948	53.531	81.131	167.386	289.773
	40	80	0.618	1.132	1.903	3.242	6.163	10.934	17.653	33.847	58.546	88.732	183.069	316.922
		90	0.601	1.103	1.853	3.157	6.001	10.647	17.189	32.959	47.009	86.403	178.263	308.603
		100	0.584	1.071	1.800	3.067	5.830	10.343	16.698	32.018	55.382	83.936	173.173	299.791
	50	90	0.630	1.156	1.943	3.310	6.291	11.162	18.020	34.552	59.766	90.580	186.882	323.523
		100	0.611	1.121	1.884	3.209	6.100	10.823	17.473	33.503	57.951	87.831	181.209	313.702
		110	0.595	1.092	1.834	3.125	5.941	10.540	17.016	32.627	56.435	85.532	176.467	305.493

Table 8.24 Minimum Refrigeration Capacity in Kilowatts for Oil Entrainment up Hot-Gas Risers (Copper Tubing, ASTM B 88M Type B, Metric Size) [2014R, Ch 1, Tbl 20] ***(Continued)***

Refrigerant	Saturated Discharge Temp., °C	Discharge Gas Temp., °C	Tubing Diameter, Nominal OD, mm											
			12	15	18	22	28	35	42	54	67	79	105	130
134a	20	60	0.469	0.860	1.445	2.462	4.681	8.305	13.408	25.709	44.469	67.396	139.050	240.718
		70	0.441	0.808	1.358	2.314	4.399	7.805	12.600	24.159	41.788	63.334	130.668	226.207
		80	0.431	0.790	1.327	2.261	4.298	7.626	12.311	23.605	40.830	61.881	127.671	221.020
	30	70	0.493	0.904	1.519	2.587	4.918	8.726	14.087	27.011	46.722	70.812	145.096	252.916
		80	0.463	0.849	1.426	2.430	4.260	8.196	13.232	25.371	43.885	66.512	137.225	237.560
		90	0.452	0.829	1.393	2.374	4.513	8.007	12.926	24.785	42.870	64.974	134.052	232.066
	40	80	0.507	0.930	1.563	2.662	5.061	8.979	14.496	27.794	48.075	72.863	150.328	260.242
		90	0.477	0.874	1.469	2.502	4.756	8.439	13.624	26.122	45.184	68.480	141.285	244.588
		100	0.465	0.852	1.432	2.439	4.637	8.227	13.281	25.466	44.048	66.759	137.735	238.443
	50	90	0.510	0.936	1.573	2.679	5.093	9.037	14.589	27.973	48.385	73.332	151.296	261.918
		100	0.479	0.878	1.476	2.514	4.779	8.480	13.690	26.248	45.402	68.811	141.969	245.772
		110	0.467	0.857	1.441	2.454	4.665	8.278	13.364	25.624	44.322	67.173	138.590	239.921

Notes:
1. Refrigeration capacity in kilowatts is based on saturated evaporator at –5 °C, and condensing temperature as shown in table. For other liquid line temperatures, use correction factors in table at right.
2. Values computed using ISO 32 mineral oil for R-22, and ISO 32 ester-based oil for R-134a.

Refrigerant	Saturated Suction Temperature, °C						
	–50	–40	–30	–20	0	5	10
22	0.87	0.90	0.93	0.96	—	1.02	—
134a	—	—	—	—	1.02	1.04	1.06

Table 8.25 Suction, Discharge, and Liquid Capacities in Kilowatts for Ammonia (Single- or High-Stage Applications) [2014R, Ch 2, Tbl 2]

Steel Nominal Line Size, mm	Suction Lines ($\Delta t = 0.02$ K/m) Saturated Suction Temperature, °C					Discharge Lines $\Delta t = 0.02$ K/m, $\Delta p = 684.0$ Pa/m Saturated Suction Temp., °C			Steel Nominal Line Size, mm	Liquid Lines	
	–40 $\Delta p = 76.9$	–30 $\Delta p = 116.3$	–20 $\Delta p = 168.8$	–5 $\Delta p = 276.6$	+5 $\Delta p = 370.5$	–40	–20	+5		Velocity = 0.5 m/s	$\Delta p = 450.0$
10	0.8	1.2	1.9	3.5	4.9	8.0	8.3	8.5	10	3.9	63.8
15	1.4	2.3	3.6	6.5	9.1	14.9	15.3	15.7	15	63.2	118.4
20	3.0	4.9	7.7	13.7	19.3	31.4	32.3	33.2	20	110.9	250.2
25	5.8	9.4	14.6	25.9	36.4	59.4	61.0	62.6	25	179.4	473.4
32	12.1	19.6	30.2	53.7	75.4	122.7	126.0	129.4	32	311.0	978.0
40	18.2	29.5	45.5	80.6	113.3	184.4	189.4	194.5	40	423.4	1469.4
50	35.4	57.2	88.1	155.7	218.6	355.2	364.9	374.7	50	697.8	2840.5
65	56.7	91.6	140.6	248.6	348.9	565.9	581.4	597.0	65	994.8	4524.8
80	101.0	162.4	249.0	439.8	616.9	1001.9	1029.3	1056.9	80	1536.3	8008.8
100	206.9	332.6	509.2	897.8	1258.6	2042.2	2098.2	2154.3	10	3.9	63.8
125	375.2	601.8	902.6	1622.0	2271.4	3682.1	3783.0	3884.2	—	—	—
150	608.7	975.6	1491.4	2625.4	3672.5	5954.2	6117.4	6281.0	—	—	—
200	1252.3	2003.3	3056.0	5382.5	7530.4	12 195.3	12 529.7	12 864.8	—	—	—
250	2271.0	3625.9	5539.9	9733.7	13619.6	22 028.2	22 632.2	23 237.5	—	—	—
300	3640.5	5813.5	8873.4	15568.9	21787.1	35 239.7	36 206.0	37 174.3	—	—	—

Notes:

1. Table capacities are in kilowatts of refrigeration.

   Δp = pressure drop due to line friction, Pa/m

   Δt = corresponding change in saturation temperature, K/m

2. Line capacity for other saturation temperatures Δt and equivalent lengths L_e

$$\text{Line capacity} = \text{Table capacity}\left(\frac{\text{Table } L_e}{\text{Actual } L_e} \times \frac{\text{Actual } \Delta t}{\text{Table } \Delta t}\right)^{0.55}$$

3. Saturation temperature Δt for other capacities and equivalent lengths L_e

$$\Delta t = \text{Table } \Delta t \left(\frac{\text{Actual } L_e}{\text{Table } L_e}\right)\left(\frac{\text{Actual capacity}}{\text{Table capacity}}\right)^{1.8}$$

4. Values are based on 30°C condensing temperature. Multiply table capacities by the following factors for other condensing temperatures:

Condensing Temperature, °C	Suction Lines	Discharge Lines
20	1.04	0.86
30	1.00	1.00
40	0.96	1.24
50	0.91	1.43

5. Liquid line capacities based on −5°C suction.

Table 8.26 Liquid Ammonia Line Capacities (Capacity in tons of refrigeration, except as noted) [2014R, Ch 2, Tbl 3]

Nominal Size, in.	Pumped Liquid Overfeed Ratio			High-Pressure Liquid at 3 psi[a]	Hot-Gas Defrost[a]	Equalizer High Side[b]	Thermosiphon Lubricant Cooling Lines Gravity Flow,[c] 1000 Btu/h		
	3:1	4:1	5:1				Supply	Return	Vent
1/2	10	7.5	6	30	—	—	—	—	—
3/4	22	16.5	13	69	9–15	50	—	—	—
1	43	32.5	26	134	16–27	100	—	—	—
1 1/4	93.5	70	56	286	28–38	150	—	—	—
1 1/2	146	110	87.5	439	39–64	225	200	120	203
2	334	250	200	1016	65–107	300	470	300	362
2 1/2	533	400	320	1616	108–152	500	850	530	638
3	768	576	461	2886	153–246	1000	1312	870	1102
4	1365	1024	819	—	247–411	2000	2261	1410	2000
5	—	—	—	—	—	—	3550	2214	3624
6	—	—	—	—	—	—	5130	3200	6378
8	—	—	—	—	—	—	8874	5533	11596

Source: Wile (1977).

[a]Rating for hot-gas branch lines under 100 ft with minimum inlet pressure of 105 psig, defrost pressure of 70 psig, and –20°F evaporators designed for a 10°F temperature differential.

[b] Line sizes based on experience using total system evaporator tons.

[c] From Frick Co. (1995). Values for line sizes above 4 in. are extrapolated.

Lubricants In Refrigerant Systems

Oil in refrigerant compressors lubricates, acts as coolant, and seals the suction from the discharge side. Oil mixes well with hydrocarbon refrigerants at higher temperatures; miscibility is reduced as temperature lowers. Oil leaves the compressor and dissolves into the refrigerant in the condenser, and passes through the liquid line to the evaporator where it separates. In higher temperature systems, it returns by gravity or is dragged by the returning vapor. Low temperature halocarbon systems need an oil separator at the compressor discharge. Oil return up vertical piping requires significant refrigerant velocity. Lubricants are generally not miscible with ammonia and separate easily out of the liquid. Oil separators at the discharge of compressors are essential. Oil must be periodically or continuously removed and returned to the compressor.

There is no ideal lubricant. For halocarbon refrigerants, there are mineral lubricants, both naphthenic and paraffinic, and synthetic lubricants, ester and glycol. Viscosity grades required vary with the temperature and the solubility of the refrigerant in the lubricant. Additives are used to enhance lubricant properties or impact new characteristics. They may be polar compounds, polymers, or compounds containing active elements such as sulfur or phosphorus. Lubricants should be dry; normally almost all hydrocarbon lubricants have a moisture content of about 30 ppm. Synthetic lubricants polyalkylene glycols (PAGs) are used commonly in automobile R-134a systems; polyalphaolefins (PAOs) are mainly used an immiscible oil in ammonia systems; polyol esters are used with HFC refrigerants in all types of compressors. Low pour point is essential for oils in ammonia systems.

When retrofitting to a new refrigerant, follow the recommendations of the equipment manufacturer on the lubricants that are suitable for use.

Mixing lubricants can cause serious problems; to extend equipment life, it is important to use lubricants approved or specified by the system or compressor manufacturer.

Table 8.27 Secondary Coolant Performance Comparisons [2014R, Ch 13, Tbl 1]

Secondary Coolant	Concentration (by Weight), %	Freeze Point, °C	L/(s·kW)[a]	Pressure Drop,[b] kPa	Heat Transfer Coefficient[c] h_i, W/(m^2·K
Propylene glycol	39	–20.6	0.0459	20.064	1164
Ethylene glycol	38	–21.6	0.0495	16.410	2305
Methanol	26	–20.7	0.0468	14.134	2686
Sodium chloride	23	–20.6	0.0459	15.858	3169
Calcium chloride	22	–22.1	0.0500	16.685	3214
Aqua ammonia	14	–21.7	0.0445	16.823	3072
Trichloroethylene	100	–86.1	0.1334	14.548	2453
d-Limonene	100	–96.7	0.1160	10.204	1823
Methylene chloride	100	–96.7	0.1146	12.824	3322
R-11	100	–111.1	0.1364	14.341	2430

[a]Based on inlet secondary coolant temperature at pump of 3.9°C.
[b]Based on one length of 4.9 m tube with 26.8 mm ID and use of Moody Chart (1944) for an average velocity of 2.13 m/s. Input/output losses equal $V^2\rho/2$ for 2.13 m/s velocity. Evaluations are at a bulk temperature of –6.7°C and a temperature range of 5.6 K.
[c]Based on curve fit equation for Kern's (1950) adaptation of Sieder and Tate's (1936) heat transfer equation using 4.9 m tube for L/D = 181 and film temperature of 2.8°C lower than average bulk temperature with 2.134 m/s velocity.

Table 8.28 Relative Pumping Energy Required* [2014R, Ch 13, Tbl 3]

Secondary Coolant	Energy Factor
Aqua ammonia	1.000
Methanol	1.078
Propylene glycol	1.142
Ethylene glycol	1.250
Sodium chloride	1.295
Calcium chloride	1.447
d-Limonene	2.406
Methylene chloride	3.735
Trichloroethylene	4.787
Aqua ammonia	1.000
Methanol	1.078
R-11	5.022

*Based on same pump pressure, refrigeration load, –6.7°C average temperature, 6 K range, and freezing point (for water-based secondary coolants) 11 to 13 K below lowest secondary coolant temperature.

9. REFRIGERANT SAFETY

(For more guidance, see ANSI/ASHRAE Standard 15, *Safety Standard for Refrigeration Systems*, and ANSI/ASHRAE Standard 34, *Designation and Safety Classification of Refrigerants.*)

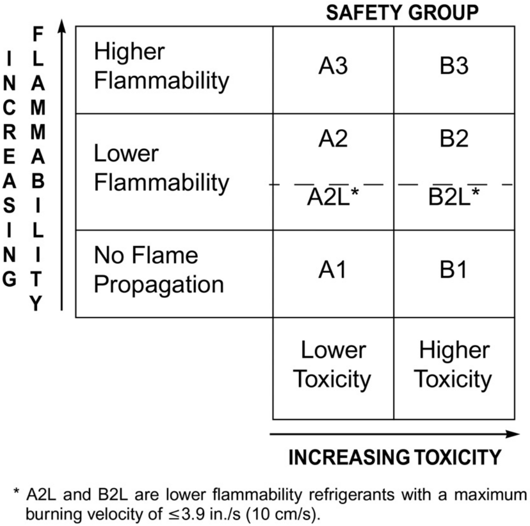


Figure 9.1 Refrigerant Safety Group Classification [Std 34-2016, Fig 1]

Refrigerant Safety

Table 9.1 Refrigerant Data and Safety Classifications [Std 34-2016, Tbl 4-1]

Refrigerant Number	Chemical Name[a,b]	Chemical Formula[a]	OEL[f], ppm v/v	Safety Group	RCL[c] (ppm v/v)	RCL[c] (lb/Mcf)	RCL[c] (g/m^3)	Highly Toxic or Toxic[d] Under Code Classification
Methane Series								
11	trichlorofluoromethane	CCl_3F	C1000	A1	1100	0.39	6.2	Neither
12	dichlorodifluoromethane	CCl_2F_2	1000	A1	18,000	5.6	90	Neither
12B1	bromochlorodifluoromethane	$CBrClF_2$						Neither
13	chlorotrifluoromethane	$CClF_3$	1000	Al				Neither
13B1	bromotrifluoromethane	$CBrF_3$	1000	Al				Neither
14[e]	tetrafluoromethane (carbon tetrafluoride)	CF_4	1000	Al	110,000	25	400	Neither
21	dichlorofluoromethane	$CHCl_2F$		B1				Toxic
22	chlorodifluoromethane	$CHClF_2$	1000	Al	59,000	13	210	Neither
23	trifluoromethane	CHF_3	1000	Al	41,000	7.3	120	Neither
30	dichloromethane (methylene chloride)	CH_2Cl_2		B1				Neither
31	chlorofluoromethane	CH_2ClF						Neither
32	difluoromethane (methylene fluoride)	CH_2F_2	1000	A2L	36,000	4.8	77	Neither
40	chloromethane (methyl chloride)	CH_3Cl		B2				Toxic
41	fluoromethane (methyl fluoride)	CH_3F						Neither
50	methane	CH_4	1000	A3				Neither
Ethane Series								
113	1,1,2-trichloro-1,2,2-trifluoroethane	CCl_2FCClF_2	1000	A1	2600	1.2	20	Neither
114	1,2-dichloro-1,1,2,2-tetrafluoroethane	$CClF_2CClF_2$	1000	A1	20,000	8.7	140	Neither
115[g]	chloropentafluoroethane	$CClF_2CF_3$	1000	A1	120,000	47	760	Neither
116[e]	hexafluoroethane	CF_3CF_3	1000	A1	97,000	34	550	Neither
123	2,2-dichloro-1,1,1-trifluoroethane	$CHCl_2CF_3$	50	B1	9100	3.5	57	Neither
124	2-chloro-1,1,1,2-tetrafluoroethane	$CHClFCF_3$	1000	A1	10,000	3.5	56	Neither
125[e]	pentafluoroethane	CHF_2CF_3	1000	A1	75,000	23	370	Neither
134a	1,1,1,2-tetrafluoroethane	CH_2FCF_3	1000	A1	50,000	13	210	Neither
141b	1,1-dichloro-1-fluoroethane	CH_3CCl_2F	500		2600	0.78	12	Neither
142b	1-chloro-1,1-difluoroethane	CH_3CClF_2	1000	A2	20,000	5.1	83	Neither
143a	1,1,1-trifluoroethane	CH_3CF_3	1000	A2L	21,000	4.5	70	Neither
152a	1,1-difluoroethane	CH_3CHF_2	1000	A2	12,000	2.0	32	Neither
170	ethane	CH_3CH_3	1000	A3	7000	0.54	8.7	Neither
Ethers								
E170	methoxymethane (dimethyl ether)	CH_3OCH_3	1000	A3	8500	1.0	16	Neither
Propane								
218[e]	octafluoropropane	$CF_3CF_2CF_3$	1000	A1	90,000	43	690	Neither
227ea[e]	1,1,1,2,3,3,3-heptafluoropropane	CF_3CHFCF_3	1000	A1	84,000	36	580	Neither
236fa	1,1,1,3,3,3-hexafluoropropane	$CF_3CH_2CF_3$	1000	A1	55,000	21	340	Neither
245fa	1,1,1,3,3-pentafluoropropane	$CHF_2CH_2CF_3$	300	B1	34,000	12	190	Neither
290	propane	$CH_3CH_2CH_3$	1000	A3	5300	0.56	9.5	Neither
Cyclic Organic Compounds								
C318	octafluorocyclobutane	$-(CF_2)_4-$	1000	A1	80,000	41	660	Neither

Table 9.1 Refrigerant Data and Safety Classifications [Std 34-2016, Tbl 4-1] ***(Continued)***

Refrigerant Number	Chemical Name[a,b]	Chemical Formula[a]	OEL[f], ppm v/v	Safety Group	RCL[c] (ppm v/v)	RCL[c] (lb/Mcf)	RCL[c] (g/m^3)	Highly Toxic or Toxic[d] Under Code Classification
Miscellaneous Organic Compounds								
Hydrocarbons								
600	butane	$CH_3CH_2CH_2CH_3$	1000	A3	1000	0.15	2.4	Neither
600a	2-methylpropane (isobutane)	$CH(CH_3)_2CH_3$	1000	A3	4000	0.59	9.6	Neither
601	pentane	$CH_3CH_2CH_2CH_2CH_3$	600	A3	1000	0.18	2.9	Neither
601a	2-methylbutane (isopentane)	$(CH_3)_2CHCH_2CH_3$	600	A3	1000	0.18	2.9	Neither
Oxygen compounds								
610	ethoxyethane (ethyl ether)	$CH_3CH_2OCH_2CH_3$	400					Neither
611	methyl formate	$HCOOCH_3$	100	B2				Neither
Sulfur compounds								
620	(Reserved for future assignment)							
Nitrogen Compounds								
630	methanamine (methyl amine)	CH_3NH_2						Toxic
631	ethanamine (ethyl amine)	$CH_3CH_2(NH_2)$						Neither
Inorganic Compounds								
702	hydrogen	H_2		A3				Neither
704	helium	He		A1				Neither
717	ammonia	NH_3	25	B2L	320	0.014	0.22	Neither
718	water	H_2O		A1				Neither
720	neon	Ne		A1				Neither
728	nitrogen	N_2		A1				Neither
732	oxygen	O_2						Neither
740	argon	Ar		A1				Neither
744	carbon dioxide	CO_2	5000	A1	30,000	3.4	54	Neither
744A	nitrous oxide	N_2O						Neither
764	sulfur dioxide	SO_2		B1				Neither
Unsaturated Organic Compounds								
1130(E)	trans-1,2-dichloroethene	CHCl=CHCl	200	B1	100	0.25	4	Neither
1150	ethene (ethylene)	CH_2=CH_2	200	A3				Neither
1233zd(E)	trans-1-chloro-3,3,3-trifluoro-1-propene	CF_3CH=CHCl	800	A1	16,000	5.3	85	Neither
1234yf	2,3,3,3-tetrafluoro-1-propene	CF_3CF=CH_2	500	A2L	16,000	4.7	75	Neither
1234ze(E)	trans-1,3,3,3-tetrafluoro-1-propene	CF_3CH=CFH	800	A2L	16,000	4.7	75	Neither
1270	propene (propylene)	CH_3CH=CH_2	500	A3	1000	0.11	1.7	Neither
1336mzz(Z)	cis-1,1,1,4,4,4-hexaflouro-2-butene	$CF_3CHCHCF_3$	500	A1	13,000	5.4	87	Neither

a. The chemical name and chemical formula are not part of this standard. Chemical names conform to IUPAC nomenclature[14,15] except where shortened, unambiguous names are used following ASHRAE Standard 34 convention.
b. The preferred chemical name is followed by the popular name in parentheses.
c. Data taken from J.M. Calm, "ARTI Refrigerant Database," Air- Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, July 2001; J.M. Calm, "Toxicity Data to Determine Refrigerant Concentration Limits," Report DE/CE 23810-110, Air- Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, September 2000; J.M. Calm, "The Toxicity of Refrigerants," *Proceedings of the 1996 International Refrigeration Conference*, Purdue University, West Lafayette, IN, pp. 157–62, 1996; D.P. Wilson and R.G. Richard, "Determination of Refrigerant Lower Flammability Limits (LFLs) in Compliance with Proposed Addendum p to ANSI/ASHRAE Standard 34-1992 (1073-RP)," *ASHRAE Transactions* 2002, 108(2); D.W. Coombs, "HFC-32 Assessment of Anesthetic Potency in Mice by Inhalation," Huntingdon Life Sciences Ltd., Huntingdon, Cambridgeshire, England, February 2004 and amendment February 2006; D.W. Coombs, "HFC-22 An Inhalation Study to Investigate the Cardiac Sensitization Potential in the Beagle Dog," Huntingdon Life Sciences Ltd., Huntingdon, Cambridgeshire, England, August 2005; and other toxicity studies.
d. *Highly toxic*, *toxic*, or *neither*, where *highly toxic* and *toxic* are as defined in the *International Fire Code*, *Uniform Fire Code*, and OSHA regulations, and *neither* identifies those refrigerants having lesser toxicity than either of those groups[1,2,3].
e. At locations with altitudes higher than 4920 ft (1500 m), the ODL and RCL shall be 69,100 ppm.
f. The OELs are eight-hour TWAs, as defined in Section 3, unless otherwise noted; a "C" designation denotes a ceiling limit.
g. At locations with altitudes higher than 3300 ft (1000 m) but below or equal to 4920 ft (1500 m), the ODL and RCL shall be 112,000 ppm, and at altitudes higher than 4920 ft (1500 m), the ODL and RCL shall be 69,100 ppm.

Table 9.2 Data and Safety Classifications for Refrigerant Blends
[Std 34-2016, Tbl 4-2]

Refrigerant Number	Composition (Mass%)	Composition Tolerances	OEL[h], ppm v/v	Safety Group	RCL[a] (ppm v/v)	RCL[a] (lb/Mcf)	RCL[a] (g/m^3)	Highly Toxic or Toxic[f] Under Code Classification
Zeotropes								
400	R-12/114 (must be specified)			A1				Neither
	(50.0/50.0)		1000	A1	28,000	10	160	
	(60.0/40.0)		1000	A1	30,000	11	170	
401A	R-22/152a/124 (53.0/13.0/34.0)	(±2.0/+0.5, –1.5/±1.0)	1000	A1	27,000	6.6	110	Neither
401B	R-22/152a/124 (61.0/11.0/28.0)	(±2.0/+0.5, –1.5/±1.0)	1000	A1	30,000	7.2	120	Neither
401C	R-22/152a/124 (33.0/15.0/52.0)	(±2.0/+0.5, –1.5/±1.0)	1000	A1	20,000	5.2	84	Neither
402A	R-125/290/22 (60.0/2.0/38.0)	(±2.0/+0.1, –1.0/±2.0)	1000	A1	66,000	17	270	Neither
402B	R-125/290/22 (38.0/2.0/60.0)	(±2.0/+0.1, –1.0/±2.0)	1000	A1	63,000	15	240	Neither
403A	R-290/22/218 (5.0/75.0/20.0)	(+0.2, –2.0/±2.0/±2.0)	1000	A2	33,000	7.6	120	Neither
403B[g]	R-290/22/218 (5.0/56.0/39.0)	(+0.2, –2.0/±2.0/±2.0)	1000	A1	70,000	18	290	Neither
404A[i]	R-125/143a/134a (44.0/52.0/4.0)	(±2.0/±1.0/±2.0)	1000	A1	130,000	31	500	Neither
405A	R-22/152a/142b/C318 (45.0/7.0/5.5/42.5)	Individual components = (±2.0/±1.0/±1.0/±2.0); sum of R-152a and R-142b = (+0.0, –2.0)	1000		57,000	16	260	Neither
406A	R-22/600a/142b (55.0/4.0/41.0)	(±2.0/±1.0/±1.0)	1000	A2	21,000	4.7	25	Neither
407A[g]	R-32/125/134a (20.0/40.0/40.0)	(±2.0/±2.0/±2.0)	1000	A1	83,000	19	300	Neither
407B[g]	R-32/125/134a (10.0/70.0/20.0)	(±2.0/±2.0/±2.0)	1000	A1	79,000	21	330	Neither
407C[g]	R-32/125/134a (23.0/25.0/52.0)	(±2.0/±2.0/±2.0)	1000	A1	81,000	18	290	Neither
407D	R-32/125/134a (15.0/15.0/70.0)	(±2.0/±2.0/±2.0)	1000	A1	68,000	16	250	Neither
407E[g]	R-32/125/134a (25.0/15.0/60.0)	(±2.0/±2.0/±2.0)	1000	A1	80,000	17	280	Neither
407F	R-32/125/134a (30.0/30.0/40.0)	(±2.0/±2.0/±2.0)	1000	A1	95,000	20	320	Neither
407G	R-32/125/134a (2.5/2.5/95.0)	(±0.5/±0.5/±1.0)	1000	A1	52,000	13	210	Neither
408A[g]	R-125/143a/22 (7.0/46.0/47.0)	(±2.0/±1.0/±2.0)	1000	A1	95,000	21	340	Neither
409A	R-22/124/142b (60.0/25.0/15.0)	(±2.0/±2.0/±1.0)	1000	A1	29,000	7.1	110	Neither
409B	R-22/124/142b (65.0/25.0/10.0)	(±2.0/±2.0/±1.0)	1000	A1	30,000	7.3	120	Neither
410A[i]	R-32/125 (50.0/50.0)	(+0.5, –1.5/+1.5, –0.5)	1000	A1	140,000	26	420	Neither
410B[i]	R-32/125 (45.0/55.0)	(±1.0/±1.0)		A1	140,000	27	430	Neither
411A[e]	R-1270/22/152a (1.5/87.5/11.0)	(+0.0, –1.0/+2.0, –0.0/+0.0, –1.0)	990	A2	14,000	2.9	46	Neither
411B[e]	R-1270/22/152a (3.0/94.0/3.0)	(+0.0, –1.0/+2.0, –0.0/+0.0, –1.0)	980	A2	13,000	2.8	45	Neither
412A	R-22/218/142b (70.0/5.0/25.0)	(±2.0/±2.0/±1.0)	1000	A2	22,000	5.1	82	Neither
413A	R-218/134a/600a (9.0/88.0/3.0)	(±1.0/±2.0/+0.0, –1.0)	1000	A2	22,000	5.8	94	Neither
414A	R-22/124/600a/142b (51.0/28.5/4.0/16.5)	(±2.0/±2.0/±0.5/+0.5, –1.0)	1000	A1	26,000	6.4	100	Neither
414B	R-22/124/600a/142b (50.0/39.0/1.5/9.5)	(±2.0/±2.0/±0.5/+0.5, –1.0)	1000	A1	23,000	6.0	95	Neither
415A	R-22/152a (82.0/18.0)	(±1.0/±1.0)	1000	A2	14,000	2.9	47	Neither
415B	R-22/152a (25.0/75.0)	(±1.0/±1.0)	1000	A2	12,000	2.1	34	Neither
416A[e]	R-134a/124/600 (59.0/39.5/1.5)	(+0.5, –1.0/+1.0, –0.5/+1.0, –0.2)	1000	A1	14,000	3.9	62	Neither
417A[e]	R-125/134a/600 (46.6/50.0/3.4)	(±1.1/±1.0/+0.1, –0.4)	1000	A1	13,000	3.5	56	Neither

Table 9.2 Data and Safety Classifications for Refrigerant Blends
[Std 34-2016, Tbl 4-2] ***(Continued)***

Refrigerant Number	Composition (Mass%)	Composition Tolerances	OEL[h], ppm v/v	Safety Group	RCL[a] (ppm v/v)	RCL[a] (lb/Mcf)	RCL[a] (g/m³)	Highly Toxic or Toxic[f] Under Code Classification
Zeotropes (*continued*)								
417B	R-125/134a/600 (79.0/18.3/2.7)	(±1.0/±1.0/+0.1, –0.5)	1000	A1	15,000	4.3	70	Neither
417C	R-125/134a/600 (19.5/78.8/1.7)	(±1.0/±1.0/+0.1, –0.5)	1000	A1	21,000	5.4	87	Neither
418A	R-290/22/152a (1.5/96.0/2.5)	(±0.5/±1.0/±0.5)	1000	A2	22,000	4.8	77	Neither
419A[g]	R-125/134a/E170 (77.0/19.0/4.0)	(±1.0/±1.0/±1.0)	1000	A2	15,000	4.2	67	Neither
419B	R-125/134a/E170 (48.5/48.0/3.5)	(±1.0/±1.0/±0.5)	1000	A2	17,000	4.6	74	Neither
420A	R-134a/142b (88.0/12.0)	(+1.0, –0.0/+0.0, –1.0)	1000	A1	45,000	12	190	Neither
421A	R-125/134a (58.0/42.0)	(±1.0/±1.0)	1000	A1	61,000	17	280	Neither
421B	R-125/134a (85.0/15.0)	(±1.0/±1.0)	1000	A1	69,000	21	330	Neither
422A	R-125/134a/600a (85.1/11.5/3.4)	(±1.0/±1.0/+0.1, –0.4)	1000	A1	63,000	18	290	Neither
422B	R-125/134a/600a (55.0/42.0/3.0)	(±1.0/±1.0/+0.1, –0.5)	1000	A1	56,000	16	250	Neither
422C	R-125/134a/600a (82.0/15.0/3.0)	(±1.0/±1.0/+0.1, –0.5)	1000	A1	62,000	18	290	Neither
422D	R-125/134a/600a (65.1/31.5/3.4)	+0.9, –1.1/±1.0/+0.1, –0.4)	1000	A1	58,000	16	260	Neither
422E	R-125/134a/600a (58.0/39.3/2.7)	(±1.0/+1.7, –1.3/+0.3, –0.2)	1000	A1	57,000	16	260	Neither
423A	R-134a/227ea (52.5/47.5)	(±1.0/±1.0)	1000	A1	59,000	19	310	Neither
424A[e]	R-125/134a/600a/600/601a (50.5/47.0/0.9/1.0/0.6)	(±1.0/±1.0/+0.1, –0.2/+0.1, +0.2/+0.1, –0.2)	970	A1	23,000	6.2	100	Neither
425A	R-32/134a/227ea (18.5/69.5/12.0)	(±0.5/±0.5/±0.5)	1000	A1	72,000	16	260	Neither
426A[e]	R-125/134a/600/601a (5.1/93.0/1.3/0.6)	(±1.0/±1.0/+0.1, –0.2/+0.1, –0.2)	990	A1	20,000	5.2	83	Neither
427A	R-32/125/143a/134a (15.0/25.0/10.0/50.0)	(±2.0/±2.0/±2.0/±2.0)	1000	A1	79,000	18	290	Neither
428A	R-125/143a/290/600a (77.5/20.0/0.6/1.9)	(±1.0/±1.0/+0.1, –0.2/+0.1, –0.2)	1000	A1	83,000	23	370	Neither
429A	R-E170/152a/600a (60.0/10.0/30.0)	(±1.0/±1.0/±1.0)	1000	A3	6300	0.81	13	Neither
430A	R-152a/600a (76.0/24.0)	(±1.0/±1.0)	1000	A3	8000	1.3	21	Neither
431A	R-290/152a (71.0/29.0)	(±1.0/±1.0)	1000	A3	5500	0.69	11	Neither
432A	R-1270/E170 (80.0/20.0)	(±1.0/±1.0)	700	A3	1200	0.13	2.1	Neither
433A	R-1270/290 (30.0/70.0)	(±1.0/±1.0)	880	A3	3100	0.34	5.5	Neither
433B	R-1270/290 (5.0/95.0)	(±1.0/±1.0)	950	A3	4500	0.51	8.1	Neither
433C	R-1270/290 (25.0/75.0)	(±1.0/±1.0)	790	A3	3600	0.41	6.6	Neither
434A[g]	R-125/143a/134a/600a (63.2/18.0/16.0/2.8)	(±1.0/±1.0/±1.0/+0.1, –0.2)	1000	A1	73,000	20	320	Neither
435A	R-E170/152a (80.0/20.0)	(±1.0/±1.0)	1000	A3	8500	1.1	17	Neither
436A	R-290/600a (56.0/44.0)	(±1.0/±1.0)	1000	A3	4000	0.50	8.1	Neither
436B	R-290/600a (52.0/48.0)	(±1.0/±1.0)	1000	A3	4000	0.51	8.2	Neither
437A	R-125/134a/600/601 (19.5/78.5/1.4/0.6)	(+0.5, –1.8/+1.5, –0.7/+0.1, –0.2/+0.1, –0.2)	990	A1	19,000	5.0	82	Neither
438A	R-32/125/134a/600/601a (8.5/45.0/44.2/1.7/0.6)	(+0.5, –1.5/±1.5/±1.5/+0.1, –0.2/+0.1, –0.2)	990	A1	20,000	4.9	79	Neither
439A	R-32/125/600a (50.0/47.0/3.0)	(±1.0/±1.0/±0.5)	990	A2	26,000	4.7	76	Neither

Table 9.2 Data and Safety Classifications for Refrigerant Blends
[Std 34-2016, Tbl 4-2] ***(Continued)***

Refrigerant Number	Composition (Mass%)	Composition Tolerances	OEL[h], ppm v/v	Safety Group	RCL[a] (ppm v/v)	RCL[a] (lb/Mcf)	RCL[a] (g/m^3)	Highly Toxic or Toxic[f] Under Code Classification
Zeotropes (*continued*)								
440A	R-290/134a/152a (0.6/1.6/97.8)	(±0.1/±0.6/±0.5)	1000	A2	12,000	1.9	31	Neither
441a	R-170/290/600a/600 (3.1/54.8/6.0/36.1)	(±0.3/±2.0/±0.6/±2.0)	1000	A3	3200	0.39	6.3	Neither
442A	R-32/125/134a/152a/227ea (31.0/31.0/30.0/3.0/5.0)	(±1.0/±1.0±/1.0/±0.5/±1.0)	1000	A1	100,000	21	330	Neither
443A	R-1270/290/600a (55.0/40.0/5.0)	(±2.0/±2.0/±1.2)	580	A3	1700	0.19	3.1	Neither
444A	R-32/152a/1234ze(E) (12.0/5.0/83.0)	(±1.0/±1.0/±2.0)	850	A2L	21,000	5.1	81	Neither
444B	R-32/152a/1234ze(E) (41.5/10.0/48.5)	(±1.0/±1.0/±1.0)	890	A2L	23,000	4.3	69	Neither
445A	R-744/134a/1234ze(E) (6.0/9.0/85.0)	(±1.0/±1.0/±2.0)	930	A2L	16,000	4.2	67	Neither
446A	R-32/1234ze(E)/600 (68.0/29.0/3.0)	(+0.5, –1.0/+2.0, –0.6/+0.1, –1.0)	960	A2L	16,000	2.5	39	Neither
447A	R-32/125/1234ze(E) (68.0/3.5/28.5)	(+1.5, –0.5/+1.5, –0.5/+1.0, –1.0)	900	A2L	16,000	2.6	42	Neither
447B	R-32/125/1234ze(E) (68.0/8.0/24.0)	(+1.0, –2.0/+2.0, –1.0/+1.0, –2.0)	970	A2L	30,000	23	360	Neither
448A	R-32/125/1234yf/134a/1234ze(E) (26.0/26.0/20.0/21.0/7.0)	(+0.5, –2.0/+2.0, –0.5/+0.5, –2.0/+2.0, –1.0/+0.5, –2.0)	890	A1	110,000	24	390	Neither
449A	R-32 /125 /1234yf /134a (24.3/24.7/25.3/25.7)	(+0.2, –1.0/+1.0, –0.2/+0.2, –1.0/+1.0, –0.2)	830	A1	100,000	23	370	Neither
449B	R-32/125/1234yf/134a (25.2/24.3/23.2/27.3)	(+0.3, –1.5/+1.5, –0.3/+0.3, –1.5/+1.5, –0.3)	850	A1	100,000	23	370	Neither
449C	R-32/125/1234yf/134a (20.0/20.0/31.0/29.0)	(+0.5, –1.5/+1.5, –0.5/+0.5, –1.5/+1.5, –0.5)	800	A1	98,000	23	360	Neither
450A	R-134a/1234ze(E) (42.0/58.0)	(±2.0/±2.0)	880	A1	72,000	20	320	Neither
451A	R-1234yf/134a (89.8/10.2)	(±0.2/±0.2)	520	A2L	18,000	5.3	81	Neither
451B	R-1234yf/134a (88.8/11.2)	(±0.2/±0.2)	530	A2L	18,000	5.3	81	Neither
452A	R-32/125/1234yf (11.0/59.0/30.0)	(±1.7/±1.8/+0.1, –1.0)	780	A1	10,000	27	440	Neither
452B	R-32/125/1234yf (67.0/7.0/26.0)	(±2.0/±1.5/±2.0)	870	A2L	30,000	23	360	Neither
452C	R-32/125/1234yf (12.5/61.0/26.5)	(+0.5, –1.5/±1.0/+0.5, –1.5)	800	A1	100,000	27	430	Neither
453A	R-32/125/134a/227ea/600/601a (20.0/20.0/53.8/5.0/0.6/0.6)	(±1.0/±1.0/±1.0/±0.5/+0.1, –0.2/+0.1, –0.2)	1000	A1	34,000	7.8	120	Neither
454A	R-32/1234yf (35.0/65.0)	(+2.0/–2.0, +2.0/–2.0)	690	A2L	16,000	28	450	Neither
454B	R-32/1234yf (68.9/31.1)	(+1.0/–1.0, +1.0/–1.0)	850	A2L	19,000	22	360	Neither
454C	R-32/1234yf (21.5/78.5)	(±2.0/±2.0)	620	A2L	19,000	29	460	Neither
455A	R-744/32/1234yf (3.0/21.5/75.5)	(+2.0, –1.0/+1.0, –2.0/±2.0)	650	A2L	30,000	23	380	Neither
456A	R-32/134a/1234ze(E) (6.0/45.0/49.0)	(±1.0/±1.0/±1.0)	900	A1	77,000	20	320	Neither
457A	R-32/1234yf/152a (18.0/70.0/12.0)	(+0.5, –1.5/+0.5, –1.5/+0.1, –1.9)	650	A2L	15,000	25	400	Neither
458A	R-32/125/134a/227ea/236fa (20.5/4.0/61.4/13.5/0.6)	(±0.5/±0.5/±0.5/±0.5/±0.1)	1000	A1	76,000	18	280	Neither

Table 9.2 Data and Safety Classifications for Refrigerant Blends
[Std 34-2016, Tbl 4-2] ***(Continued)***

Refrigerant Number	Composition (Mass%)	Composition Tolerances	OEL[h], ppm v/v	Safety Group	RCL[a] (ppm v/v)	RCL[a] (lb/Mcf)	RCL[a] (g/m^3)	Highly Toxic or Toxic[f] Under Code Classification
Azeotropes[b]								
500	R-12/152a (73.8/26.2)		1000	A1	30,000	7.6	120	Neither
501	R-22/12 (75.0/25.0)[c]		1000	A1	54,000	13	210	Neither
502[g]	R-22/115 (48.8/51.2)		1000	A1	73,000	21	330	Neither
503	R-23/13 (40.1/59.9)		1000					Neither
504[i]	R-32/115 (48.2/51.8)		1000		140,000	28	450	Neither
505	R-12/31 (78.0/22.0)[c]							Neither
506	R-31/114 (55.1/44.9)							Neither
507A[d,i]	R-125/143a (50.0/50.0)		1000	A1	130,000	32	520	Neither
508A[d]	R-23/116 (39.0/61.0)		1000	A1	55,000	14	220	Neither
508B	R-23/116 (46.0/54.0)		1000	A1	52,000	13	200	Neither
509A[d,g]	R-22/218 (44.0/56.0)		1000	A1	75,000	24	390	Neither
510A	R-E170/600a (88.0/12.0)	(±0.5/±0.5)	1000	A3	7300	0.87	14	Neither
511A	R-290/E170 (95.0/5.0)	(±1.0/±1.0)	1000	A3	5300	0.59	9.5	Neither
512A	R-134a/152a (5.0/95.0)	(±1.0/±1.0)	1000	A2	11,000	1.9	31	Neither
513A	R-1234yf/134a (56.0/44.0)	(±1.0/±1.0)	650	A1	72,000	20	320	Neither
513B	R-1234yf/134a (58.5/41.5)	(±0.5/±0.5)	640	A1	74,000	21	330	Neither
514A	R-1336mzz(Z)/1130 (E) (74.7/25.3)	(+1.5, –0.5/+0.5, –1.5)	320	B1	2400	0.86	14	Neither
515A	R-1234ze(E)/227ea (88.0/12.0)	(+1.0, –2.0/+2.0, –1.0)	810	A1	62,000	19	300	Neither

a. Data taken from J.M. Calm, "ARTI Refrigerant Database," Air- Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, July 2001; J.M. Calm, "Toxicity Data to Determine Refrigerant Concentration Limits," Report DE/CE 23810-110, Air- Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, September 2000; J.M. Calm, "The Toxicity of Refrigerants," *Proceedings of the 1996 International Refrigeration Conference*, Purdue University, West Lafayette, IN, pp. 157–62, 1996; D.P. Wilson and R.G. Richard, "Determination of Refrigerant Lower Flammability Limits (LFLs) in Compliance with Proposed Addendum p to ANSI/ASHRAE Standard 34-1992 (1073-RP)," *ASHRAE Transactions* 2002, 108(2); D.W. Coombs, "HFC-32 Assessment of Anesthetic Potency in Mice by Inhalation," Huntingdon Life Sciences Ltd., Huntingdon, Cambridgeshire, England, February 2004 and amendment February 2006; D.W. Coombs, "HFC-22 An Inhalation Study to Investigate the Cardiac Sensitization Potential in the Beagle Dog," Huntingdon Life Sciences Ltd., Huntingdon, Cambridgeshire, England, August 2005; and other toxicity studies.
b. Azeotropic refrigerants exhibit some segregation of components at conditions of temperature and pressure other than those at which they were formulated. The extent of segregation depends on the particular azeotrope and hardware system configuration.
c. The exact composition of this azeotrope is in question, and additional experimental studies are needed.
d. R-507, R-508, and R-509 are allowed alternative designations for R-507A, R-508A, and R-509A due to a change in designations after assignment of R-500 through R-509. Corresponding changes were not made for R-500 through R-506.
e. The RCL values for these refrigerant blends are approximated in the absence of adequate data for a component comprising less than 4% m/m of the blend and expected to have only a small influence in an acute, accidental release.
f. *Highly toxic*, *toxic*, or *neither*, where *highly toxic* and *toxic* are as defined in the *International Fire Code*, *Uniform Fire Code*, and OSHA regulations, and *neither* identifies those refrigerants having lesser toxicity than either of those groups [1,2,3].
g. At locations with altitudes higher than 4920 ft (1500 m), the ODL and RCL shall be 69,100 ppm.
h. The OELs are eight-hour TWAs as defined in Section 3 unless otherwise noted; a "C" designation denotes a ceiling limit.
i. At locations with altitudes higher than 3300 ft (1000 m) but below or equal to 4920 ft (1500 m), the ODL and RCL shall be 112, 000 ppm, and at altitudes higher than 4920 ft (1500 m), the ODL and RCL shall be 69,100 ppm.

Refrigerating Machinery Rooms

When required, the machinery room shall

- Be dimensioned so parts are accessible with space for service and maintenance.
- Have tight-fitting doors opening outward, self-closing if they open into the building, with no openings permitting passage of escaping refrigerant into the building except gasketed access panels of ductwork and air-handling equipment.
- Contain a leak detector located where refrigerant from a leak will concentrate that actuates visual and audible alarms inside the room and outside each entrance, and activates the mechanical ventilation.
- On alarm, exhaust of $Q_{cfm} = 100 \times G^{0.5}$ where G is pounds of refrigerant in the largest system, with openings for inlet air to avoid recirculation; multiple fans or multispeed fans to operate to reduce airflow for normal operation to at least 0.5 cfm per ft^2 or 20 cfm per person, and operable when occupied to limit temperature rise to 18°F above inlet air or a maximum of 122°F.
- Combustion air can be used for equipment in the machinery room only if ducted from outside the room and sealed from refrigerant entry, and a refrigerant detector is employed to shut off combustion on refrigerant leaks. (Exceptions: CO_2 or water refrigerant; or ammonia only driven by internal combustion engine.)
- Be no airflow to or from an occupied space through a machinery room unless ducted and sealed against refrigerant leaks.
- Restrict access to authorized personnel with clear signage at each entrance. If system is in an open enclosure outdoors more than 20 ft from building openings, mechanical or natural ventilation may be used; free-opening area for natural ventilation shall be $F_{sqft} = G^{0.5}$.

The total of Group A2, B2, A3, or B3 refrigerants except R-717 (ammonia) shall not exceed 1100 lb without approval of the authority having jurisdiction. Special requirements in 7.5 of Standard 15-2007 apply relative to recovered, reclaimed, or recycled refrigerants, or mixing of refrigerants, refrigerant, or lubricant conversion. Group A2, A3, B1, B2, or B3 refrigerants shall not be used in high-probability systems (where a refrigerant leak can enter occupied space) for human comfort.

Refrigerant Piping

Piping shall not be installed in elevators or other shafts that have moving objects or open into living quarters. It shall not penetrate floors except the top floor to the roof, or the basement to the first floor, unless enclosed in a gastight, fire-resistive shaft. The piping shall be enclosed in a pipe duct if inside floors.

Pressure Relief Protection

Refrigerating systems shall be protected by pressure relief devices. ANSI/ASHRAE Standard 15 covers required location and sizing. All pressure relief valves shall be marked "UV" or "VR," and all rupture members marked with data required by paragraph UG 127 of Section VIII, Division 1, of the *ASME Boiler and Pressure Vessel Code*; and fusible plugs shall be marked with the melting temperature. Generally, pressure relief devices and fusible plugs shall discharge to the atmosphere not less than 15 ft above ground and 20 ft from a window, ventilation opening, pedestrian walkway, or exit in any building.

10. REFRIGERATION

Transmission Load

The overall coefficient of heat transfer U of the wall, floor, or ceiling of a refrigerated space can be derived from:

$$U = \frac{1}{1/f_i + x_1/k_1 + x_2/k_2 + 1/f_o} \tag{10.1}$$

where

U = overall heat transfer coefficient, W/(m^2· K)
x = wall thickness, m
k = thermal conductivity of wall material, W/(m· K)
f_i = inside film or surface conductance, W/(m^2· K)
f_o = outside film or surface conductance, W/(m^2· K)

9.37 W/(m^2· K) for f_i and f_o is frequently used for still air. If the outer surface is exposed to 24 km/h wind, f_o is increased to 34 W/(m^2· K).

With thick walls and low conductivity, the resistance x/k makes U so small that $1/f$ has little effect and can be omitted from the calculation.

After establishing U, the heat gain is given by Equation 10.2:

$$q = UA\Delta t \tag{10.2}$$

where

q = heat leakage, W
A = outside area of section, m^2
Δt = difference between outside air temperature and air temperature of the refrigerated space, °C

Latent heat gain due to moisture transmission through walls, floors, and ceilings of modern-construction refrigerated facilities is negligible.

Table 10.1 Thermal Conductivity of Cold Storage Insulation
[2014R, Ch 24, Tbl 1]

Insulation	Thermal Conductivity[a] k, W/(m·K)
Polyurethane board (R-11 expanded)	0.023 to 0.026
Polyisocyanurate, cellular (R-141b expanded)	0.027
Polystyrene, extruded (R-142b)	0.035
Polystyrene, expanded (R-142b)	0.037
Corkboard[b]	0.043
Foam glass[c]	0.044

[a]Values are for a mean temperature of 24°C, and insulation is aged 180 days.
[b]Seldom used. Data are only for reference.
[c]Virtually no effects from aging.

Table 10.2 Minimum Insulation Thickness [2014R, Ch 24, Tbl 2]

Storage Temperature, °C	Expanded Polyisocyanurate Thickness	
	Northern U.S., mm	Southern U.S., mm
10 to 16	50	50
4 to 10	50	50
–4 to 4	50	75
–9 to –4	75	75
–18 to –9	75	100
–26 to –18	100	100
–40 to –26	125	125

Table 10.3 Allowance for Sun Effect [2014R, Ch 24, Tbl 3]

Typical Surface Types	East Wall, K	South Wall, K	West Wall, K	Flat Roof, K
Dark-colored surfaces				
Slate roofing	5	3	5	11
Tar roofing				
Black paint				
Medium-colored surfaces				
Unpainted wood	4	3	4	9
Brick				
Red tile				
Dark cement				
Red, gray, or green paint				
Light-colored surfaces				
White stone	3	2	3	5
Light-colored cement				
White paint				

Note: Add to the normal temperature difference for heat leakage calculations to compensate for sun effect. Do not use for air-conditioning design.

Product Load

1. Heat removed to cool from initial temperature to some lower temperature above freezing:

$$Q_1 = mc_1(t_1 - t_2) \tag{10.3}$$

2. Heat removed in cooling from the initial temperature to a freezing point of the product:

$$Q_2 = mc_1(t_1 - t_f) \tag{10.4}$$

3. Heat removed to freeze the product:

$$Q_3 = mh_{if} \tag{10.5}$$

4. Heat removed in cooling from the freezing point to the final temperature below the freezing point:

$$Q_4 = mc_2\,(t_f - t_3) \tag{10.6}$$

where

Q_1, Q_2, Q_3, Q_4	=	heat removed, kJ
m	=	weight of the product, kg
c_1	=	specific heat of the product above freezing, kJ/(kg·K)
t_1	=	initial temperature of the product above freezing, °C
t_2	=	lower temperature of the product above freezing, °C
t_f	=	freezing temperature of the product, °C
h_{if}	=	latent heat of fusion of the product, kJ/kg
c_2	=	specific heat of the product below freezing, kJ/(kg·K)
t_3	=	final temperature of the product below freezing, °C

Specific heats above and below freezing for many products are given in 2014R, Ch 19, Tbl 3.

Refrigeration system capacity for products brought into refrigerated spaces is determined from the time allotted for heat removal and assumes that the product is properly exposed to remove the heat in that time. The calculation is:

$$q = \frac{Q_2 + Q_3 + Q_4}{3600n} \tag{10.7}$$

where

q	=	product cooling load, kW
n	=	allotted time period, h

A product's latent heat of fusion is related to its water content and can be estimated by multiplying the product's percent of water (expressed as a decimal) by the water's latent heat of fusion, 334 kJ/kg. Most food products freeze in the range of –3 to –0.5°C. When the exact freezing temperature is not known, assume that it is –2.2°C.

Table 10.4 Heat Gain from Typical Electric Motors [2014R, Ch 24, Tbl 6]

				Location of Motor and Driven Equipment with Respect to Conditioned Space or Airstream		
				A	B	C
Motor Rated, kW	Motor Type	Nominal rpm	Full Load Motor Efficiency, %	Motor in, Driven Equipment in, W	Motor out, Driven Equipment in, W	Motor in, Driven Equipment out, W
0.04	Shaded pole	1500	35	105	35	70
0.06			35	170	59	110
0.09			35	264	94	173
0.12			35	340	117	223
0.19	Split phase	1750	54	346	188	158
0.25			56	439	246	194
0.37			60	621	372	249
0.56	3-Phase	1750	72	776	557	217
0.75			75	993	747	249

Table 10.5 Heat Equivalent of Occupancy [2014R, Ch 24, Tbl 7]

Refrigerated Space Temperature, °C	Heat Equivalent/Person, W
10	210
5	240
0	270
–5	300
–10	330
–15	360
–20	390

Note: Heat equivalent may be estimated by the following equation:

$$q_p = 272 - 6t$$

where t = temperature of refrigerated space, °C

Packaging Related Load

Cardboard and wood used as part of product packaging adsorb or desorb moisture, depending on air temperature and relative humidity. This moisture sorption represents a conversion between sensible and latent heat: the latent heat of sorption is countered by sensible heat transfer between the packaging and the air by convection. The heat load q_t from to the i packaging components is

$$q_t = \frac{\sum m_i c_i (t_1 - t_3)}{3600n} \tag{10.8}$$

$$q_l = \frac{\left[\frac{m(X_1 - X_3)L}{1 + X_1}\right]_{wood} + \left[\frac{m(X_1 - X_3)L}{1 + X_1}\right]_{cardboard}}{3600n} \tag{10.9}$$

where

q_l	=	total heat load, kJ
m_i	=	mass of ith packaging component, kg
c_i	=	specific heat of ith packaging component, kJ/(kg·K)
X_1	=	entering packaging component moisture content, kg/kg dry basis
X_3	=	packaging component moisture content after time n, kg/kg dry basis
L	=	latent heat of sorption, kJ/kg (2500 kJ/kg)

Typical values of c_i are given in Table 10.6. X_1 can be measured or estimated using moisture sorption isotherms based on the air temperature and relative humidity the packaging experienced before entering the refrigerated space. The moisture sorption isotherms for wood and cardboard are given in Figures 10.1 and 10.2. X_3 can be estimated using Figures 10.3 or 10.4 to get Y and

$$X_3 = X^* + (X_1 - X^*)Y \tag{10.10}$$

where

Y	=	fractional unaccomplished moisture change (Figure 10.4)
X^*	=	equilibrium packaging component moisture content, kg/kg dry basis

X^* can be estimated using the moisture sorption isotherms based on the air temperature and relative humidity in the refrigerated space using Figures 10.1 and 10.2 for wood and cardboard, respectively, where equilibrium moisture content (EMC) is plotted against equilibrium relative humidity (ERH).

Table 10.6 Typical Specific Heat Capacities of Common Packaging Materials
[2014R, Ch 24, Tbl 8]

Material	Specific Heat Capacity c, kJ/(kg·K)
Wood	1.7
Cardboard	1.4
Plastic	1.6
Aluminum	0.85
Steel	0.5

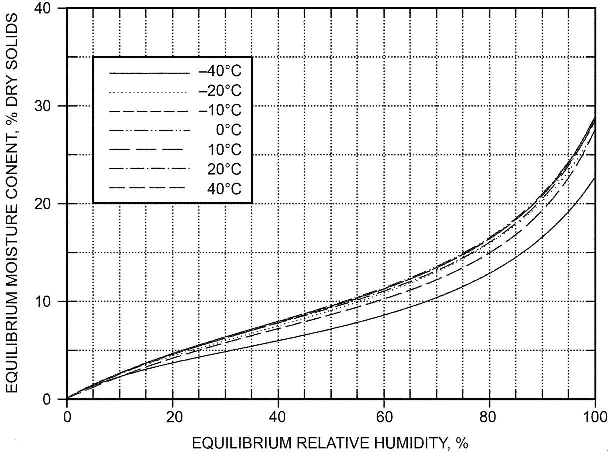


Figure 10.1 Moisture Sorption Isotherms for Wood as Function of Air Temperature and Relative Humidity [2014R, Ch 24, Fig 3]

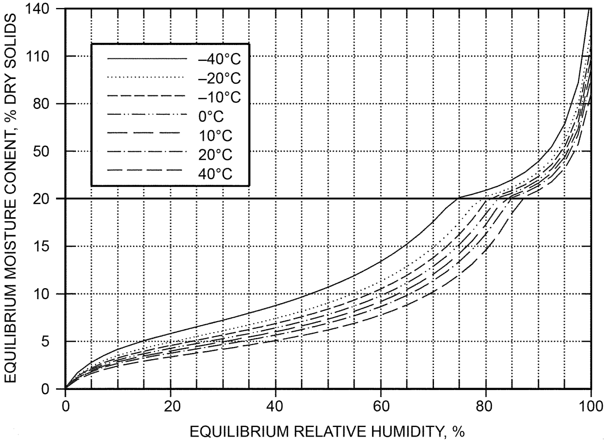
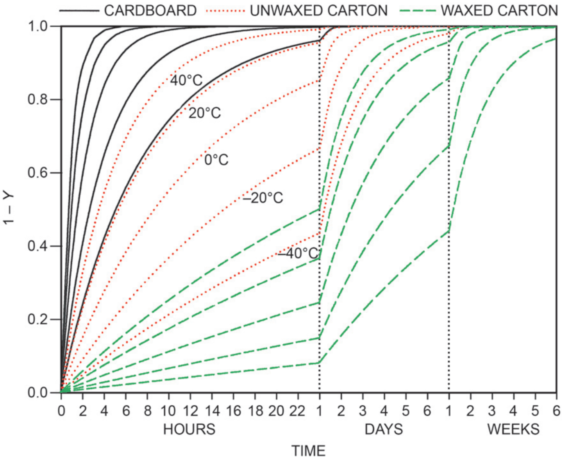


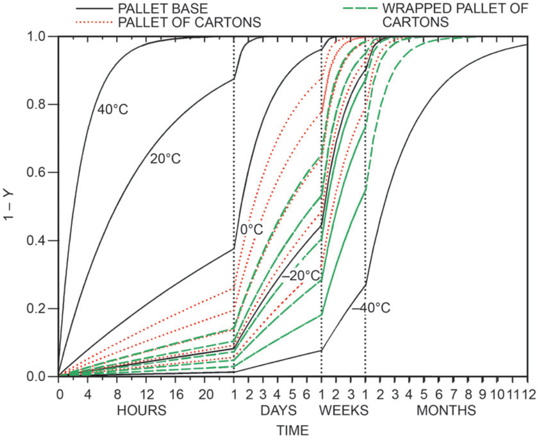
Figure 10.2 Moisture Sorption Isotherms for Cardboard as Function of Air Temperature and Relative Humidity [2014R, Ch 24, Fig 4]

Refrigeration Load



(All plots given in the same temperature order as for unwaxed carton)

Figure 10.3 Fractional Unaccomplished Moisture Change as Function of Time and Temperature for Sheets of Cardboard, Unwaxed Cartons, and Waxed Cartons
[2014R, Ch 24, Fig 5]



(All plots given in same temperature order as for pallet of cartons)

Figure 10.4 Fractional Unaccomplished Moisture Change as Function of Time and Temperature for Wooden Pallet Bases, Unwrapped Pallets of Cartons, and Wrapped Pallets of Cartons
[2014R, Ch 24, Fig 6]

Infiltration Air Load

Heat gain through doorways from air exchange is:

$$q_t = qD_tD_f(1 - E) \tag{10.11}$$

where

q_t	=	average heat gain for the 24 h or other period, kW
q	=	sensible and latent refrigeration load for fully established flow, kW
D_t	=	doorway open-time factor
D_f	=	doorway flow factor
E	=	effectiveness of doorway protective device

$$q = 0.5773790\ WH^{1.5}\ (Q_s/A)(1/R_s) \tag{10.12}$$

where

Q_s/A	=	sensible heat load of infiltration air per square foot of doorway opening as read from Figure 10.3, kW/m^2
W	=	doorway width, m
H	=	doorway height, m
R_s	=	sensible heat ratio of the infiltration air heat gain, from a psychrometric chart

Doorway open-time factor D_t can be calculated as follows:

$$D_t = \frac{(P\theta_p + 60\theta_o)}{3600\theta_d} \tag{10.13}$$

where

D_t	=	decimal portion of time doorway is open
P	=	number of doorway passages
θ_p	=	door open-close time, seconds per passage
θ_o	=	time door simply stands open, min
θ_d	=	the daily (or other) time period, h

Equipment-Related Load

Equipment-related load consists essentially of fan heat where forced air circulation is used, reheat where humidity control is provided, defrosting heat gain where defrosting occurs, and moisture evaporation where the defrosting process is exposed to refrigerated air. To accurately select heat-extracting equipment, a distinction should be made between those equipment heat loads that are felt within the refrigerated space and those that are introduced directly to the refrigerating fluid.

Equipment heat gain is usually minor at space temperatures above approximately –1°C, but may be up to 15%.

Safety Factor

Generally, a 10% safety factor is applied to the calculated load to allow for possible discrepancies between the design criteria and actual operation. Refrigeration system capacity should be sufficient to handle the load with the actual running time, allowing for defrost cycles.

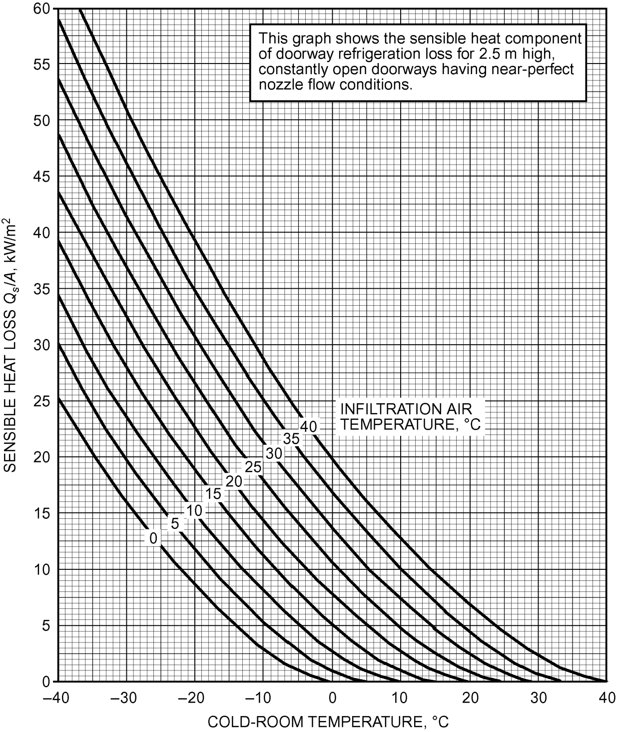


Figure 10.5 Sensible Heat Gain by Air Exchange for Continuously Open Door with Fully Established Flow [2014R, Ch 24, Fig 9]

Refrigeration Equipment

Liquid Coolers

A liquid cooler (hereafter called a cooler) is a heat exchanger A in which refrigerant is evaporated, thereby cooling a fluid (usually water or brine) circulating through the cooler.

Various types of liquid coolers and their characteristics are listed in Table 10.7 and Figures 10.6 through 10.12.

Heat transfer for liquid coolers can be expressed by the following steady-state heat transfer equation:

$$q = UA\Delta t_m \qquad (10.14)$$

where

q	=	total heat transfer rate, W
Δt_m	=	mean temperature difference, K
A	=	heat transfer surface area associated with U, m^2
U	=	overall heat transfer coefficient, $W/(m^2 \cdot K)$

The area A can be calculated if the geometry of the cooler is known. The mean temperature difference is

$$\Delta t_m = (\Delta t_1 - \Delta t_2)/\ln(\Delta t_1/\Delta t_2) \qquad (10.15)$$

where Δt_1 and Δt_2 are temperature differences between the fluids at each end of the heat exchanger.

Table 10.7 Types of Coolers

Type of Cooler	Subtype	Usual Refrigerant Feed Device	Usual Capacity Range, kW	Commonly Used Refrigerants
Direct-expansion	Shell-and-tube	Thermal expansion valve Electronic modulation valve	7 to 1800 7 to 1800	12, 22, 134a, 404A, 407C, 410A, 500, 502, 507A, 717
	Tube-in-tube	Thermal expansion valve	18 to 90	12, 22, 134a, 717
	Brazed-plate	Thermal expansion valve	2 to 700	12, 22, 134a, 404A 407C, 410A, 500, 502, 507A, 508B, 717, 744
	Semiwelded plate	Thermal expansion valve	175 to 7000	12, 22, 134a, 500, 502, 507A, 717, 744
Flooded	Shell-and-tube	Low-pressure float	90 to 7000	11, 12, 22, 113, 114
		High-pressure float	90 to 21 100	123, 134a, 500, 502, 507A, 717
		Fixed orifice(s) Weir	90 to 21 100 90 to 21 100	
	Spray shell-and-tube	Low-pressure float	180 to 35 000	11, 12, 13B1, 22
		High-pressure float	180 to 35 000	113, 114, 123, 134a
	Brazed-plate	Low-pressure float	2 to 700	12, 22, 134a, 500, 502, 507A, 717, 744
	Semiwelded plate	Low-pressure float	175 to 7000	12, 22, 134a, 500, 502, 507A, 717, 744
Baudelot	Flooded	Low-pressure float	35 to 350	22, 717
	Direct-expansion	Thermal expansion valve	18 to 90	12, 22, 134a, 717
Shell-and-coil	—	Thermal expansion valve	7 to 35	12, 22, 134a, 717

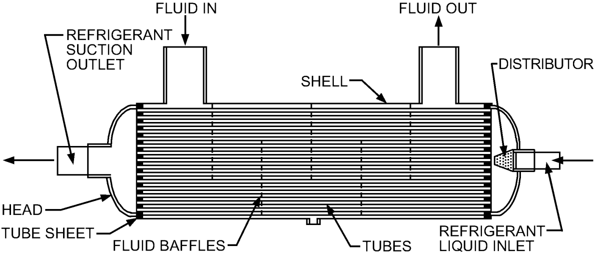


Figure 10.6 Direct-Expansion Shell-and-Tube Cooler [2016S, Ch 42, Fig 1]]

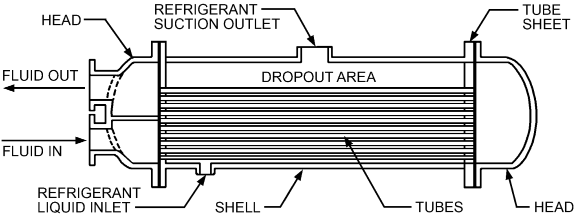


Figure 10.7 Flooded Shell-and-Tube Cooler [2016S, Ch 42, Fig 2]]

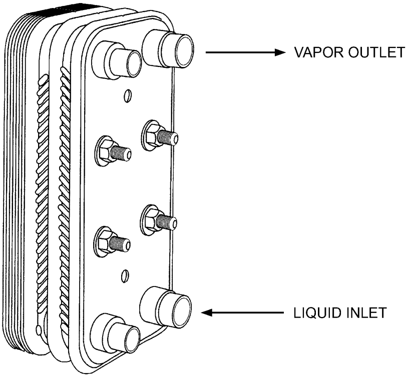


Figure 10.8 Flooded Plate Cooler [2016S, Ch 42, Fig 3]

Refrigeration Load

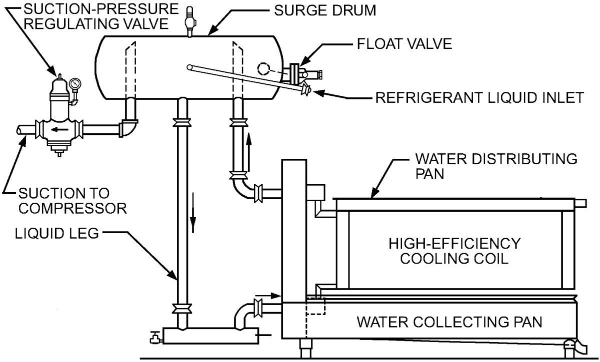


Figure 10.9 Baudelot Cooler [2016S, Ch 42, Fig 4]

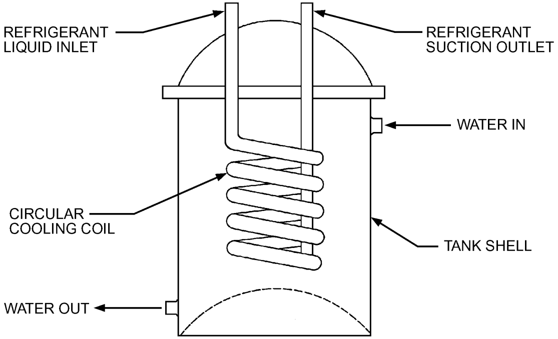


Figure 10.10 Shell-and-Coil Cooler [2016S, Ch 42, Fig 5]

Refrigeration Load

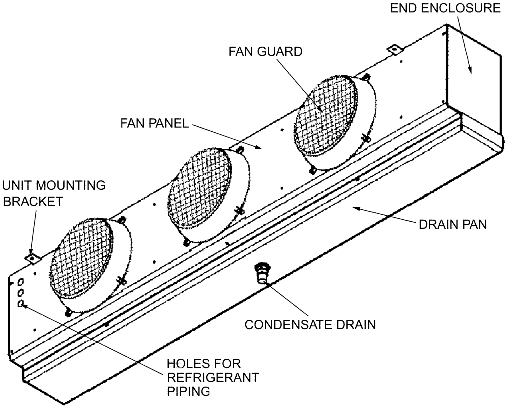


Figure 10.11 Low-Profile Cooler [2014R, Ch 14, Fig 3]

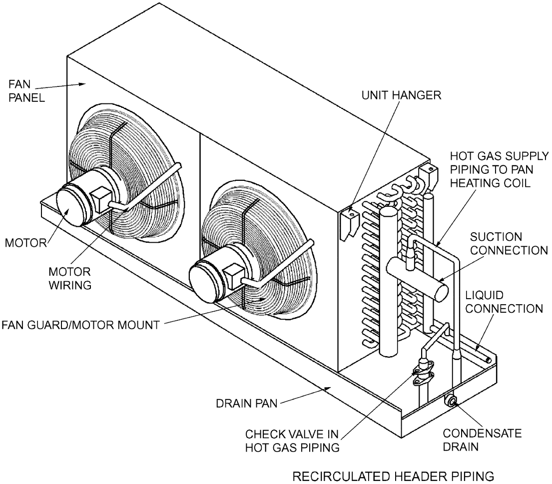


Figure 10.12 Liquid Overfeed Type Unit Cooler [2014R, Ch 14, Fig 4]

U may be calculated by one of the following equations.

Based on inside surface area:

$$U = \frac{1}{1/h_i + [A_i/(A_o h_o)] + (t/k)(A_i/A_m) + r_{fi}} \tag{10.16}$$

Based on outside surface area:

$$U = \frac{1}{[A_o/(A_i h_i)] + 1/h_o + (t/k)(A_o/A_m) + r_{fo}} \tag{10.17}$$

where

h_i = inside heat transfer coefficient based on inside surface area, $W/(m^2 \cdot K)$
h_o = outside heat transfer coefficient based on outside surface area, $W/(m^2 \cdot K)$
A_o = outside heat transfer surface area, m^2
A_i = inside heat transfer surface area, m^2
A_m = mean heat transfer area of metal wall, m^2
k = thermal conductivity of heat transfer material, $W/(m \cdot K)$
t = thickness of heat transfer surface (tube wall thickness), m
r_{fi} = fouling factor of fluid side based on inside surface area, $(m^2 \cdot K)/W$
r_{fo} = fouling factor of fluid side based on outside surface area, $(m^2 \cdot K)/W$

Note: If fluid is on inside, multiply r_{fi} by A_o/A_i to find r_{fo}.
If fluid is on outside, multiply r_{fo} by A_i/A_o to find r_{fi}.

These equations can be applied to incremental sections of the heat exchanger to include local effects on the value of U, and then the increments summed to obtain a more accurate design.

Over time, most fluids foul the fluid-side heat transfer surface, reducing the cooler's overall heat transfer coefficient. If fouling is expected to be a problem, a mechanically cleanable cooler should be used, such as a flooded, Baudelot, or cleanable direct-expansion tube-in-tube cooler. Direct-expansion shell-and-tube, shell-and-coil, and brazed-plate coolers can be cleaned chemically. Flooded coolers and direct-expansion tube-in-tube coolers with enhanced fluid-side heat transfer surfaces tend to be self-cleaning because of high fluid turbulence, so a smaller fouling factor can probably be used for these coolers. Research shows that negligible fouling occurs in closed-loop evaporator tubes at 1 to 1.5 m/s and 2.1 m/s water velocities. AHRI Standard 480 discusses fouling calculations.

The refrigerant side of the cooler is not subject to fouling, and a fouling factor need not be included for that side.

Typically, the t/k term in Equations 10.16 and 10.17 may be negligible for material with high thermal conductivity. However, with low-thermal-conductivity material or thick-walled tubing, it may become significant. Refer to Chapter 4 of the 2017 *ASHRAE Handbook—Fundamentals* and to Chapter 39 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* for further details.

Pressure drop is usually minimal in Baudelot and shell-and-coil coolers but must be considered in direct-expansion and flooded coolers. Both direct-expansion and flooded coolers rely on turbulent fluid flow to improve heat transfer. This turbulence is obtained at the expense of pressure drop.

For air-conditioning, pressure drop is commonly limited to 70 kPa to keep pump size and energy cost reasonable. For flooded coolers, compare also Chapter 39 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* for a discussion of pressure drop for flow in tubes. Pressure drop for fluid flow in shell-and-tube direct-expansion coolers depends greatly on tube and baffle geometry. The following equation projects the change in pressure drop caused by a change in flow:

$$\text{New pressure drop} = \text{Original pressure drop}\left[\frac{\text{New rate}}{\text{Original rate}}\right]^{1.8} \tag{10.18}$$

The refrigerant-side pressure drop must be considered for direct-expansion, shell-and-coil, brazed-plate, and (sometimes) Baudelot coolers. When there is a pressure drop on the refrigerant side, the refrigerant inlet and outlet pressures and corresponding saturated temperature are different. This difference changes the mean temperature difference, which affects the total heat transfer rate. If pressure drop is high, expansion valve operation may be affected because of reduced pressure drop across the valve. This pressure drop varies, depending on the refrigerant used, operating temperature, and type of tubing.

When the fluid being cooled is electrically conductive, the system must be grounded to prevent electrochemical corrosion.

The constant superheat thermal expansion valve is the most common control used, located directly upstream of the cooler.

In flooded coolers, an orifice is often used as the throttling device between condenser and cooler.

Freeze prevention must be considered for coolers operating near the fluid's freezing point. In some coolers, freezing causes extensive damage. Two methods can be used for freeze protection: (1) hold saturated suction pressure above the fluid freezing point or (2) shut the system off if fluid temperature approaches the freezing point.

If the cooler is used only when ambient temperature is above freezing, drain the fluid from the cooler for cold weather. Alternatively, if the cooler is used year-round, the following methods can be used to prevent freezing:

- Heat tape or other heating device to keep cooler above freezing
- For water, adding an appropriate amount of ethylene glycol
- Continuous pump operation

Most compressors discharge a small percentage of oil in the discharge gas. This oil mixes with condensed refrigerant in the condenser and flows to the cooler. Because the oil is nonvolatile, it does not evaporate and may collect in the cooler.

In direct-expansion coolers, gas velocity in the tubes and suction gas header is usually sufficient to carry oil from the cooler into the suction line. From there, with proper piping design, it can be carried back to the compressor. At light load and low temperature, oil may gather in the superheat section of the cooler, detracting from performance. For this reason, operating refrigerant circuits at light load for long periods should be avoided, especially under low-temperature conditions.

In flooded coolers, vapor velocity above the tube bundle is usually insufficient to return oil up the suction line, and oil tends to accumulate in the cooler. With time, depending on the compressor oil loss rate, oil concentration in the cooler may become large. When concentration exceeds about 1%, heat transfer performance may be adversely affected if enhanced tubing is used.

It is common in flooded coolers to take some oil-rich liquid and return it to the compressor on a continuing basis, to establish a rate of return equal to the compressor oil loss rate.

Cooler maintenance centers around (1) safety and (2) cleaning the fluid side. Periodically inspect the cooler for any weakening of its pressure boundaries. The manufacturer or a service organization experienced in cooler maintenance should have details for cleaning.

A cooler operating at a saturated suction temperature lower than the ambient-air dew point should be insulated to prevent condensation.

Forced-Circulation Air Coolers

A cooling coil and a motor-driven fan are the basic components, and coil defrosting means are added for low-temperature operations where coil frosting might impede performance. Blow-through direct-drive propeller fans are most common, but for long throws, draw-through configuration is preferred. For loads above 0°C, coil spacing is usually 240 to 320 fins per metre; below 0°C a maximum of 160 fins per metre is preferred. Even distribution of halocarbon refrigerant is usually attained in direct-expansion coils by refrigerant distributors. Units in larger refrigeration systems are often liquid-pumped recirculating types with orifice disks.

Defrost for coils and drain pans of low-temperature units may be hot-gas, electric, or water. Usually defrosting is done with the fan off. Control of defrost is usually by microprocessor, with a thermostat mounted within the coil. Usually a rise to 7°C returns the unit to the operating cycle. Drain lines should be well-pitched, insulated, and trapped outside the refrigerated space.

Capacities of air coolers are usually based on the temperature difference between inlet air and refrigerant in the coil. The higher the TD, the lower the space relative humidity. Between 5°C and 9°C TD is usual, except for packaged products and workrooms where TD of 14°C is common. Low-temperature units generally have TD below 8°C for system economics and limiting defrost frequency.

Most frequent control of refrigerant flow is an expansion valve, most frequently thermostatic type. Electric expansion valves, requiring a valve, controller, and control sensor, are also available.

Large refrigerating systems more frequently have flooded evaporators, most often low-side float valves. Refrigerant valves opening or closing flow are usually solenoid valves. Larger flows may require pilot-operated solenoid valves. When it is desired to limit compressor motor load during pulldown, an evaporator pressure regulating valve may be used to limit compressor suction pressure.

11. AIR-CONDITIONING LOAD DATA

Cooling Loads

Obtain appropriate weather data and select design conditions. In addition to the conventional dry-bulb with mean coincident wet-bulb, also consider dew-point with mean coincident dry-bulb, particularly with spaces requiring large amounts of outdoor air or close control of moisture. Select indoor dry-bulb, wet-bulb, and ventilation rate, including permissible variations and control limits. Consider proposed schedules of occupancy, lighting, and processes that contribute to the internal load. Several different times of day and months must frequently be analyzed to determine the peak load time. See the appendix for climatic design conditions for selected locations. Chapter 14, Climatic Design Information, of the 2017 *ASHRAE Handbook—Fundamentals* has more extensive design data specific to 818 worldwide locations.

ANSI/ASHRAE/ACCA Standard 183-2007 sets the minimum standards for nonresidential load calculations.

Currently there are two ASHRAE cooling load calculation methods. The first is the Heat Balance (HB) method, whose equations are coded in a generic computer program linked to a user interface program. The source code for these programs is in the ASHRAE Load Calculation Toolkit.

The second method is the Radiant Time Series (RTS) method, a simplification of the heat balance method, still requiring a complex computer program for a multiroom building.

Due to the variation in heat transfer coefficients, precision of construction, and manner of actual building operation, a cooling load calculation can never be more than a good estimate of the actual load.

To design and size components of central air-conditioning systems, more than the cooling load is needed. Type of system, fan energy and location, direct heat loss and gain, duct leakage, heat extracted from lights, and type of return system must all be considered.

Heating Loads

Similar calculations to cooling load are made, but temperatures outside conditioned spaces are usually lower than space temperatures maintained. Solar heat gains, and internal heat gains are not included and thermal storage of building structure or content is usually ignored. This is usually sufficient to cope with a worst-case situation. There is very often need for cooling in cold months, for perimeter spaces with high solar heat gain and interior spaces with significant heat gain.

Previous Cooling Load Calculation Methods

Procedures described in Chapters 17 and 18 of the 2017 *ASHRAE Handbook–Fundamentals* are the most current and scientifically derived means for estimating cooling load for a defined building space, but methods in earlier editions of the ASHRAE Handbook are valid for many applications. These earlier procedures are simplifications of the Heat Balance principles, and their use requires experience to deal with atypical or unusual circumstances. In fact, any cooling or heating load estimate is no better than the assumptions used to define conditions and parameters such as physical makeup of the various envelope surfaces, conditions of occupancy and use, and ambient weather conditions. Experience of the practitioner can never be ignored.

The primary difference between the HB and RTS methods and the older methods is the newer methods' direct approach, compared to the simplifications necessitated by the limited computer capability available previously.

The **transfer function method (TFM)**, for example, required many calculation steps. It was originally designed for energy analysis with emphasis on daily, monthly, and annual energy use, and thus was more oriented to average hourly cooling loads than peak design loads.

The **total equivalent temperature differential method with time averaging (TETD/TA)** has been a highly reliable (if subjective) method of load estimating since its initial presentation in the 1967 *Handbook of Fundamentals*. Originally intended as a manual method of calculation, it proved suitable only as a computer application because of the need to calculate an extended profile of hourly heat gain values, from which radiant components had to be averaged over a time representative of the general mass of the building involved. Because perception of thermal storage characteristics of a given building is almost entirely subjective, with little specific information for the user to judge variations, the TETD/TA method's primary usefulness has always been to the experienced engineer.

The **cooling load temperature differential method with solar cooling load factors (CLTD/CLF)** attempted to simplify the two-step TFM and TETD/TA methods into a single-step technique that proceeded directly from raw data to cooling load without intermediate conversion of radiant heat gain to cooling load. A series of factors were taken from cooling load calculation results (produced by more sophisticated methods) as "cooling load temperature differences" and "cooling load factors" for use in traditional conduction ($q = UA\Delta t$) equations. The results are approximate cooling load values rather than simple heat gain values. The simplifications and assumptions used in the original work to derive those factors limit this method's applicability to those building types and conditions for which the CLTD/CLF factors were derived; the method should not be used beyond the range of applicability.

The TFM, TETD/TA, and CLTD/CLF procedures have not been invalidated or discredited. Experienced engineers have successfully used them in millions of buildings around the world. The accuracy of cooling load calculations in practice depends primarily on the availability of accurate information and the design engineer's judgment in the assumptions made in interpreting the available data. Those factors have much greater influence on a project's success than does the choice of a particular cooling load calculation method.

The primary benefit of HB and RTS calculations is their somewhat reduced dependency on purely subjective input (e.g., determining a proper time-averaging period for TETD/TA; ascertaining appropriate safety factors to add to the rounded-off TFM results; determining whether CLTD/CLF factors are applicable to a specific unique application). However, using the most up-to-date techniques in real-world design still requires judgment on the part of the design engineer and care in choosing appropriate assumptions, just as in applying older calculation methods.

Table 11.1 Summary of Load Sources and Equations for Estimating Space Design Cooling Load

Load Source	Equation	Reference, Table, Description
External		
Roof	$q = UA(\mathrm{CLTD})$	Design heat transmission coefficients, Table 11.7 Areas calculated from plans CLTD, Table 11.8, p. 214
Walls	$q = UA(\mathrm{CLTD})$	Design heat transmission coefficients, Table 11.7 Areas calculated from plans CLTD, Table 11.10
Glass Conduction	$q = UA(\mathrm{CLTD})$	Glass area calculated from plans U-factors, pg. 202 CLTD for conduction load through glass, pg. 202
Glass Solar	$q = A(\mathrm{SC})\mathrm{SCL}$	Solar cooling load (SCL) factors, Table 11.11 Net glass area from plans Shading coefficients for combination of glass and internal shading, Table 11.12 Compute shaded area from building projections Externally shaded glass: use north orientation data
Partitions, Ceilings, Floors	$q = UA(\mathrm{TD})$	Design heat transmission coefficients, Table 11.7 Area calculated from plans
Internal		
Lights	q = INPUT	Input rating from electrical plans or lighting fixture data, Table 11.14
People		
Sensible	q_s = No. (Sens. H.G.)	Number of people in space Sensible heat gain from occupants, Table 11.13
Latent	q_l = No. (Lat. H.G.)	Latent heat gain from occupants
Equipment and Appliances	q_s = HEAT GAIN	Recommended rate of heat gain, Tables 11.15–11.32
Power	q = HEAT GAIN	p. 224
Infiltration Air	Q = L/s	
Sensible	$q_s = 120Q\,\Delta t$	Inside-outside air temperature difference, °C
Latent	$q_l = 3.0Q\,\Delta W$	Inside-outside air humidity ratio difference, g/kW
Total	$q = 1.20Q\,\Delta h$	Inside-outside air enthalpy difference, kJ/kg

CAUTION: Approximate data—Use for preliminary computations only. See *Load Calculation Applications Manual* for more details.

Heat Flow Q Through Building Materials

(In addition to heat flow through building materials the resistance of surfaces and air spaces must be included in calculating U-factors.)

$$Q\ (\mathrm{W}) = U \times \text{Area}\ (\mathrm{m}^2) \times \text{temperature difference (K)} \tag{11.1}$$

where U = overall coefficient of heat transmission, $\mathrm{W/(m^2 \cdot K)}$, of materials + interior and exterior resistances:

$$1/U = \Sigma R \text{ (resistance of components)} \tag{11.2}$$

For multiple layers of homogeneous materials, R values are added in series:

$$1/U = R_{cold\ surface} + R_1 + R_2 + R_n \ldots + R_{warm\ surface} \tag{11.3}$$

For wood stud walls, studs 400 mm on center (series and parallel):

$$1/U = R_{cold\ surface} + \left\{\frac{+\ 0.25\ R_{stud}}{+\ 0.75\ R_{stud\ space}}\right\} + R_{warm\ surface} \tag{11.4}$$

(Plus, in series, $R_{insulation}$, R_{siding}, $R_{wallboard}$, etc.)

For metal framed construction, heat flow through the metal causes thermal bridging, increasing the U-factor significantly.

Conductive Heat Flow Through Glazing

Solar radiation gain through glazing is usually more significant in cooling load calculations than conductive heat gain. Solar heat gain is neglected in heating load calculations.

Conductive heat flow through glazing including surface resistance (approximate data)

Single glazing	$U = 6.2$
Double glazing	$U = 3.1$
Triple glazing	$U = 1.9$

Table 11.2 Thermal Resistances of Plane Air Spaces,[a,b,c] $(m^2 \cdot K)/W$ [2017F, Ch 26, Tbl 3]

Position of Air Space	Direction of Heat Flow	Air Space Mean Temp.[d], °C	Air Space Temp. Diff.,[d] K	13 mm Air Space[c] 0.03	0.05	0.2	0.5	0.82	20 mm Air Space[c] 0.03	0.05	0.2	0.5	0.82
Horiz.	Up	32.2	5.6	0.37	0.36	0.27	0.17	0.13	0.41	0.39	0.28	0.18	0.13
		10.0	16.7	0.29	0.28	0.23	0.17	0.13	0.30	0.29	0.24	0.17	0.14
		10.0	5.6	0.37	0.36	0.28	0.20	0.15	0.40	0.39	0.30	0.20	0.15
		–17.8	11.1	0.30	0.30	0.26	0.20	0.16	0.32	0.32	0.27	0.20	0.16
		–17.8	5.6	0.37	0.36	0.30	0.22	0.18	0.39	0.38	0.31	0.23	0.18
		–45.6	11.1	0.30	0.29	0.26	0.22	0.18	0.31	0.31	0.27	0.22	0.19
		–45.6	5.6	0.36	0.35	0.31	0.25	0.20	0.38	0.37	0.32	0.26	0.21
Vertical	Horiz.	32.2	5.6	0.43	0.41	0.29	0.19	0.14	0.62	0.57	0.37	0.21	0.15
		10.0	16.7	0.45	0.43	0.32	0.22	0.16	0.51	0.49	0.35	0.23	0.17
		10.0	5.6	0.47	0.45	0.33	0.22	0.16	0.65	0.61	0.41	0.25	0.18
		–17.8	11.1	0.50	0.48	0.38	0.26	0.20	0.55	0.53	0.41	0.28	0.21
		–17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.66	0.63	0.46	0.30	0.22
		–45.6	11.1	0.51	0.50	0.41	0.31	0.24	0.51	0.50	0.42	0.31	0.24
		–45.6	5.6	0.56	0.55	0.45	0.33	0.26	0.65	0.63	0.51	0.36	0.27
Horiz.	Down	32.2	5.6	0.44	0.41	0.29	0.19	0.14	0.62	0.58	0.37	0.21	0.15
		10.0	16.7	0.47	0.45	0.33	0.22	0.16	0.66	0.62	0.42	0.25	0.18
		10.0	5.6	0.47	0.45	0.33	0.22	0.16	0.68	0.63	0.42	0.26	0.18
		–17.8	11.1	0.52	0.50	0.39	0.27	0.20	0.74	0.70	0.50	0.32	0.23
		–17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.75	0.71	0.51	0.32	0.23
		–45.6	11.1	0.57	0.55	0.45	0.33	0.26	0.81	0.78	0.59	0.40	0.30
		–45.6	5.6	0.58	0.56	0.46	0.33	0.26	0.83	0.79	0.60	0.40	0.30

Effective Emittance ε_{eff}[d,e] applies to columns 0.03–0.82.

[a]See Chapter 25. Thermal resistance values were determined from $R = 1/C$, where $C = h_c + \varepsilon_{eff} h_r$, h_c is conduction/convection coefficient, $\varepsilon_{eff} h_r$ is radiation coefficient $\approx 0.227\varepsilon_{eff}[(t_m + 273)/100]^3$, and t_m is mean temperature of air space.

[b]Values apply for ideal conditions (i.e., air spaces of uniform thickness bounded by plane, smooth, parallel surfaces with no air leakage to or from the space). **This table should not be used for hollow siding or profiled cladding.**

[c]A single resistance value cannot account for multiple air spaces; each air space requires a separate resistance calculation that applies only for established boundary conditions. Resistances of horizontal spaces with heat flow downward are substantially independent of temperature difference.

[d]Interpolation is permissible for other values of mean temperature, temperature difference, and effective emittance ε_{eff}. Interpolation and moderate extrapolation for air spaces greater than 90 mm are also permissible.

[e]Effective emittance ε_{eff} of air space is given by $1/\varepsilon_{eff} = 1/\varepsilon_1 + 1/\varepsilon_2 - 1$, where ε_1 and ε_2 are emittances of surfaces of air space (see 2017F, Ch 26, Tbl 2). **Also, oxidation, corrosion, and accumulation of dust and dirt can dramatically increase surface emittance. Emittance values of 0.05 should only be used where the highly reflective surface can be maintained over the service life of the assembly.**

Table 11.3 Surface Film Coefficients/Resistances [2017F, Ch 26, Tbl 10]

Position of Surface	Direction of Heat Flow	Surface Emittance, ε					
		Nonreflective ε = 0.90		Reflective			
				ε = 0.20		ε = 0.05	
Indoor		h_i	R_i	h_i	R_i	h_i	R_i
Horizontal	Upward	9.26	0.11	5.17	0.19	4.32	0.23
Sloping at 45°	Upward	9.09	0.11	5.00	0.20	4.15	0.24
Vertical	Horizontal	8.29	0.12	4.20	0.24	3.35	0.30
Sloping at 45°	Downward	7.50	0.13	3.41	0.29	2.56	0.39
Horizontal	Downward	6.13	0.16	2.10	0.48	1.25	0.80
Outdoor (any position)		h_o	R_o				
Wind (for winter) at 6.7 m/s	Any	34.0	0.030	—	—	—	—
Wind (for summer) at 3.4 m/s	Any	22.7	0.044	—	—	—	—

Notes:

1. Surface conductance h_i and h_o measured in W/(m^2·K); resistance R_i and R_o in (m^2·K)/W.
2. No surface has both an air space resistance value and a surface resistance value.
3. Conductances are for surfaces of the stated emittance facing virtual blackbody surroundings at same temperature as ambient air. Values based on surface/air temperature difference of 5.6 K and surface temperatures of 21°C.
4. See Chapter 4 of *ASHRAE Handbook—Fundamentals* for more detailed information.
5. Condensate can have significant effect on surface emittance (see 2017F, Ch 26, Tbl 2). Also, oxidation, corrosion, and accumulation of dust and dirt can dramatically increase surface emittance. Emittance values of 0.05 should only be used where highly reflective surface can be maintained over the service life of the assembly.

Table 11.4 European Surface Film Coefficients/Resistances [2017F, Ch 26, Tbl 11]

Position of Surface	Direction of Heat Flow	*h*, W/(m^2·K)	*R*, (m^2·K)/W
Indoors			
Horizontal, sloping to 45°	Upward	10	0.1
	Downward	6	0.17
Vertical, sloping beyond 45°	Any direction	7.7	0.13
Outdoors		25	0.04

Table 11.5 Emissivity of Various Surfaces and Effective Emittances of Facing Air Spaces[a] [2017F, Ch 26, Tbl 2]

Surface	Average Emissivity ε	Effective Emittance ε_{eff} of Air Space	
		One Surface's Emittance ε; Other, 0.9	Both Surfaces' Emittance ε
Aluminum foil, bright	0.05	0.05	0.03
Aluminum foil, with condensate just visible (>0.5 g/m²)	0.30[b]	0.29	—
Aluminum foil, with condensate clearly visible (>2.0 g/m²)	0.70[b]	0.65	—
Aluminum sheet	0.12	0.12	0.06
Aluminum-coated paper, polished	0.20	0.20	0.11
Brass, nonoxidized	0.04	0.038	0.02
Copper, black oxidized	0.74	0.41	0.59
Copper, polished	0.04	0.038	0.02
Iron and steel, polished	0.2	0.16	0.11
Iron and steel, oxidized	0.58	0.35	0.41
Lead, oxidized	0.27	0.21	0.16
Nickel, nonoxidized	0.06	0.056	0.03
Silver, polished	0.03	0.029	0.015
Steel, galvanized, bright	0.25	0.24	0.15
Tin, nonoxidized	0.05	0.047	0.026
Aluminum paint	0.50	0.47	0.35
Building materials: wood, paper, masonry, nonmetallic paints	0.90	0.82	0.82
Regular glass	0.84	0.77	0.72

[a]Values apply in 4 to 40 μm range of electromagnetic spectrum. Also, oxidation, corrosion, and accumulation of dust and dirt can dramatically increase surface emittance. Emittance values of 0.05 should only be used where the highly reflective surface can be maintained over the service life of the assembly. Except as noted, data from VDI (1999).
[b]Values based on data in Bassett and Trethowen (1984).

Table 11.6 Effective Thermal Resistance of Ventilated Attics[a] (Summer Condition)

Ventilation Air Temp., °C	Sol-Air[e] Temp., °C	Not Ventilation[b]		Natural Ventilation		Power Ventilation[c]					
		Ventilation Rate, L/s per m^2									
		0		0.5		2.5		5.1		7.6	
		Ceiling Resistance R[d], $K \cdot m^2/W$									
		1.8	3.5	1.8	3.5	1.8	3.5	1.8	3.5	1.8	3.5
Part A. Nonreflective Surfaces											
	49	0.33	0.33	0.49	0.60	1.11	1.64	1.69	2.82	1.94	3.52
27	60	0.33	0.33	0.49	0.62	1.14	1.76	1.72	2.99	2.11	3.70
	71	0.33	0.33	0.49	0.63	1.18	1.94	1.76	3.17	2.29	3.87
	49	0.33	0.33	0.44	0.49	0.81	1.18	1.07	1.76	1.21	2.29
32	60	0.33	0.33	0.46	0.55	0.92	1.39	1.34	2.11	1.51	2.64
	71	0.33	0.33	0.48	0.60	1.02	1.58	1.50	2.46	1.76	2.99
	49	0.33	0.33	0.39	0.40	0.58	0.77	0.70	1.06	0.72	1.21
38	60	0.33	0.33	0.42	0.48	0.74	1.07	1.02	1.53	1.14	1.76
	71	0.33	0.33	0.46	0.56	0.88	1.34	1.27	1.94	1.46	2.29
Part B. Reflective Surfaces[f]											
	49	1.14	1.14	1.43	1.55	2.29	2.99	2.99	4.40	3.34	5.28
27	60	1.14	1.14	1.44	1.58	2.46	3.17	3.17	4.58	3.52	5.46
	71	1.14	1.14	1.46	1.62	2.64	3.17	3.34	4.75	3.70	5.63
	49	1.14	1.14	1.32	1.41	1.76	2.29	2.11	2.99	2.29	3.34
32	60	1.14	1.14	1.36	1.46	2.11	2.64	2.46	3.52	2.82	3.87
	71	1.14	1.14	1.39	1.51	2.29	2.82	2.82	3.87	3.17	4.40
	49	1.14	1.14	1.23	1.30	1.41	1.76	1.50	2.11	1.55	2.11
38	60	1.14	1.14	1.28	1.37	1.76	2.11	1.94	2.64	2.11	2.82
	71	1.14	1.14	1.34	1.44	1.94	2.46	2.29	3.17	2.64	3.52

[a]Although the term effective resistance is commonly used when there is attic ventilation, this table includes values for situations with no ventilation. The effective resistance of the attic added to the resistance (1/U) of the ceiling yields the effective resistance of this combination based on sol-air and room temperatures. These values apply to wood frame construction with a roof deck and roofing that has a conductance of 5.7 $W/(m^2 \cdot K)$.

[b]This condition cannot be achieved in the field unless extreme measures are taken to tightly seal the attic.

[c]Based on air discharging outward from attic.

[d]When determining ceiling resistance, do not add the effect of a reflective surface facing the attic, as it is accounted for in Part B of this table.

[e]Roof surface temperature rather than sol-air temperature can be used if0.04 is subtracted from the attic resistance shown.

[f]Surfaces with effective emittance $\epsilon_{eff} = 0.05$ between ceiling joists facing attic space.

Table 11.7 Building and Insulating Materials: Design Values[a]

[2017F, Ch 26, Tbl 1]

Description	Density, kg/m³	Conductivity[b] k, W/(m·K)	Resistance R, (m²·K)/W	Specific Heat c_p, kJ/(kg·K)
Insulating Materials				
Blanket and batt[c,d]				
Glass-fiber batts				0.8
	7.5 to 8.2	0.046 to 0.048	—	—
	9.8 to 12	0.040 to 0.043	—	—
	13 to 14	0.037 to 0.039	—	—
	22	0.033	—	—
Rock and slag wool batts	—	—	—	0.8
	32 to 37	0.036 to 0.037	—	—
	45	0.033 to 0.035	—	—
Mineral wool, felted	16 to 48	0.040	—	—
	16 to 130	0.035	—	—
Board and slabs				
Cellular glass	120	0.042	—	0.8
Cement fiber slabs, shredded wood with				
Portland cement binder	400 to 430	0.072 to 0.076	—	—
with magnesia oxysulfide binder	350	0.082	—	1.3
Glass fiber board	—	—	—	0.8
	24 to 96	0.033 to 0.035	—	—
Expanded rubber (rigid)	64	0.029	—	1.7
Extruded polystyrene, smooth skin	—	—	—	1.5
aged per Can/ULC Standard S770-2003	22 to 58	0.026 to 0.029	—	—
aged 180 days	22 to 58	0.029		
European product	30	0.030		
aged 5 years at 24°C	32 to 35	0030	—	—
blown with low global warming potential (GWP) (<5) blowing agent		0.035 to 0.036	—	—
Expanded polystyrene, molded beads	—	—	—	1.5
	16 to 24	0.035 to 0.037	—	—
	29	0.033	—	—
Mineral fiberboard, wet felted	160	0.037	—	0.8
Rock wool board	—	—	—	0.8
floors and walls	64 to 130	0.033 to 0.036	—	—
roofing	160 to 180.	0.039 to 0.042	—	0.8
Acoustical tile[e]	340 to 370	0.052 to 0.053	—	0.6 to 0.8
Perlite board	140	0.052	—	—
Polyisocyanurate	—	—	—	1.5
unfaced, aged per Can/ULC Standard S770-2003	26 to 37	0.023 to 0.025	—	—
with foil facers, aged 180 days	—	0.022 to 0.023	—	—
Phenolic foam board with facers, aged	—	0.020 to 0.023	—	—
Loose fill				
Cellulose fiber, loose fill	—	—	—	1.4
attic application up to 100 mm	16 to 19	0.045 to 0.046	—	—
attic application > 100 mm	19 to 26	0.039 to 0.040	—	—
wall application, dense packed	56	0.039 to 0.040	—	—
Perlite, expanded	32 to 64	0.039 to 0.045	—	1.1
	64 to 120	0.045 to 0.052	—	—
	120 to 180	0.052 to 0.061	—	—
Glass fiber[d]				
attics, ~100 to 600 mm	6.4 to 8.0	0.052 to 0.055	—	—
attics, ~600 to 1100 mm	8 to 9.6	0.049 to 0.052	—	—
closed attic or wall cavities	29 to 37	0.035 to 0.036	—	—
Rock and slag wool[d]				
attics, ~90 to 115 mm	24 to 26	0.049	—	—
attics, ~125 to 430 mm	24 to 29	0.046 to 0.048	—	—
closed attic or wall cavities	64	0.039 to 0.042	—	—
Vermiculite, exfoliated	112 to 131	0.068	—	1.3
	64 to 96	0.063	—	—
Spray-applied				
Cellulose, sprayed into open wall cavities	26 to 42	0.039 to 0.040	—	—
Glass fiber, sprayed into open wall or attic cavities	16	0.039 to 0.042	—	—
	29 to 37	0.033 to 0.037	—	—
Polyurethane foam	—	—	—	1.5
low density, open cell	7.2 to 10	0.037 to 0.042	—	—
medium density, closed cell, aged 180 days	30 to 51	0.020 to 0.029	—	—

Table 11.7 Building and Insulating Materials: Design Values[a]
[2017F, Ch 26, Tbl 1] ***(Continued)***

Description	Density, kg/m^3	Conductivity[b] k, W/(m·K)	Resistance R, (m^2·K)/W	Specific Heat c_p, kJ/(kg·K)
Building Board and Siding				
Board				
Asbestos/cement board	1900	0.57	—	1.00
Cement board	1150	0.25	—	0.84
Fiber/cement board	1400	0.25	—	0.84
	1000	0.19	—	0.84
	400	0.07	—	1.88
	300	0.06	—	1.88
Gypsum or plaster board	640	0.16	—	1.15
Oriented strand board (OSB)9 to 11 mm	650	—	0.11	1.88
12.7 mm	650	—	0.12	1.88
Plywood (douglas fir)12.7 mm	460	—	0.14	1.88
15.9 mm	540	—	0.15	1.88
Plywood/wood panels19.0 mm	450	—	0.19	1.88
Vegetable fiber board	650	—	0.11	1.88
sheathing, regular density12.7 mm	290	—	0.23	1.30
intermediate density12.7 mm	350	—	0.19	1.30
nail-based sheathing12.7 mm	400	—	0.19	1.30
shingle backer9.5 mm	290	—	0.17	1.30
sound deadening board12.7 mm	240	—	0.24	1.26
tile and lay-in panels, plain or acoustic	290	0.058	—	0.59
laminated paperboard	480	0.072	—	1.38
homogeneous board from repulped paper	480	0.072	—	1.17
Hardboard				
medium density	800	0.105	—	1.30
high density, service-tempered grade and service grade	880	0.12	—	1.34
high density, standard-tempered grade	1010	0.144	—	1.34
Particleboard				
low density	590	0.102	—	1.30
medium density	800	0.135	—	1.30
high density	1000	1.18	—	—
underlayment 15.9 mm	640	—	1.22	1.21
Waferboard	700	0.072	—	1.88
Shingles				
Asbestos/cement	1900	—	0.037	—
Wood, 400 mm, 190 mm exposure	—	—	0.15	1.30
Wood, double, 400 mm, 300 mm exposure	—	—	0.21	1.17
Wood, plus ins. backer board 8 mm	—	—	0.25	1.30
Siding				—
Asbestos/cement, lapped 6.4 mm	—	—	0.037	1.01
Asphalt roll siding	—	—	0.026	1.47
Siding				
Asphalt insulating siding (12.7 mm bed)	—	—	0.26	1.47
Hardboard siding 11 mm		—	—	0.12
Wood, drop, 200 mm 25 mm	—	—	0.14	1.17
Wood, bevel				
200 mm, lapped13 mm	—	—	0.14	1.17
250 mm, lapped19 mm	—	—	0.18	1.17
Wood, plywood, lapped 9.5 mm	—	—	0.10	1.22
Aluminum, steel, or vinyl,[h, i] over sheathing			—	
hollow-backed	—	—	0.11	1.22[i]
insulating-board-backed 9.5 mm	—	—	0.32	1.34
foil-backed 9.5 mm	—	—	0.52	—
Architectural (soda-lime float) glass	2500	1.0	—	0.84
Building Membrane				
Vapor-permeable felt	—	—	0.011	—
Vapor: seal, 2 layers of mopped 0.73 kg/m^2 felt	—	—	0.21	—
Vapor: seal, plastic film	—	—	Negligible	—
Finish Flooring Materials				
Carpet and rebounded urethane pad 19 mm	110	—	0.42	—
Carpet and rubber pad (one-piece) 9.5 mm	320	—	0.12	—
Pile carpet with rubber pad 9.5 to 12.7 mm	290	—	0.28	—
Linoleum/cork tile 6.4 mm	465	—	0.09	—
PVC/rubber floor covering	—	0.40	—	—
rubber tile 25 mm	1900	—	0.06	—
terrazzo 25 mm	—	—	0.014	0.80

Table 11.7 Building and Insulating Materials: Design Values[a]
[2017F, Ch 26, Tbl 1] ***(Continued)***

Description	Density, kg/m³	Conductivity[b] k, W/(m·K)	Resistance R, (m²·K)/W	Specific Heat c_p, kJ/(kg·K)
Metals (See 2013F, Ch 33, Tbl 3)				
Roofing				
Asbestos/cement shingles	1920	—	0.037	1.00
Asphalt (bitumen with inert fill)	1600	0.43	—	—
	1900	0.58	—	—
	2300	1.15	—	—
Asphalt roll roofing	920	—	0.027	1.51
Asphalt shingles	920	—	0.078	1.26
Built-up roofing 10 mm	920	—	0.059	1.47
Mastic asphalt (heavy, 20% grit)	950	0.19	—	—
Reed thatch	270	0.09	—	—
Roofing felt	2250	1.20	—	—
Slate 13 mm	—	—	0.009	1.26
Straw thatch	240	0.07	—	—
Wood shingles, plain and plastic-film-faced	—	—	0.166	1.30
Plastering Materials				
Cement plaster, sand aggregate	1860	0.72	—	0.84
Sand aggregate 10 mm	—	—	0.013	0.84
20 mm	—	—	0.026	0.84
Gypsum plaster	1120	0.38	—	—
	1280	0.46	—	—
Lightweight aggregate 13 mm		720	—	0.056
16 mm		720	—	0.066
on metal lath 19 mm	—	—	0.083	—
Perlite aggregate	720	0.22	—	1.34
Sand aggregate	1680	0.81	—	0.84
on metal lath 19 mm	—	—	0.023	—
Vermiculite aggregate	480	0.14	—	—
	600	0.20	—	—
	720	0.25	—	—
	840	0.26	—	—
	960	0.30	—	—
Perlite plaster	400	0.08	—	—
	600	0.19	—	—
Pulpboard or paper plaster	600	0.07	—	—
Sand/cement plaster, conditioned	1560	0.63	—	—
Sand/cement/lime plaster, conditioned	1440	0.48	—	—
Sand/gypsum (3:1) plaster, conditioned	1550	0.65	—	—
Masonry Materials				
Masonry units				
Brick, fired clay	2400	1.21 to 1.47	—	—
	2240	1.07 to 1.30	—	—
	2080	0.92 to 1.12	—	—
	1920	0.81 to 0.98	—	0.80
	1760	0.71 to 0.85	—	—
	1600	0.61 to 0.74	—	—
	1440	0.52 to 0.62	—	—
	1280	0.43 to 0.53	—	—
	1120	0.36 to 0.45	—	—
Clay tile, hollow				
1 cell deep 75 mm	—	—	0.14	0.88
100 mm	—	—	0.20	—
2 cells deep 150 mm	—	—	0.27	—
200 mm	—	—	0.33	—
250 mm	—	—	0.39	—
3 cells deep 300 mm	—	—	0.44	—
Lightweight brick	800	0.20	—	—
	770	0.22	—	—
Concrete blocks[f, g]				
Limestone aggregate				
~200 mm, 16.3 kg, 2200 kg/m³ concrete, 2 cores	—	—	—	—
with perlite-filled cores	—	—	0.37	—
~300 mm, 25 kg, 2200 kg/m³ concrete, 2 cores	—		—	—
with perlite-filled cores	—	—	0.65	—

Table 11.7 Building and Insulating Materials: Design Values[a]
[2017F, Ch 26, Tbl 1] ***(Continued)***

Description	Density, kg/m^3	Conductivity[b] k, W/(m·K)	Resistance R, (m^2·K)/W	Specific Heat c_p, kJ/(kg·K)
Normal-weight aggregate (sand and gravel)				
~200 mm, 16 kg, 2100 kg/m^3 concrete, 2 or 3 cores…	—	—	0.20 to 0.17	0.92
with perlite-filled cores	—	—	0.35	—
with vermiculite-filled cores	—	—	0.34 to 0.24	—
~300 mm, 22.7 kg, 2000 kg/m^3 concrete, 2 cores	—	—	0.217	0.92
Medium-weight aggregate (combinations of normal and lightweight aggregate)				
~200 mm, 13 kg, 1550 to 1800 kg/m^3 concrete, 2 or 3 cores	—	—	0.30 to 0.22	—
with perlite-filled cores	—	—	0.65 to 0.41	—
with vermiculite-filled cores	—	—	0.58	—
with molded-EPS-filled (beads) cores	—	—	0.56	—
with molded EPS inserts in cores	—	—	0.47	—
Low-mass aggregate (expanded shale, clay, slate or slag, pumice)				
~150 mm, 7 1/2 kg, 1400 kg/m^2 concrete, 2 or 3 cores	—	—	0.34 to 0.29	—
with perlite-filled cores	—	—	0.74	—
with vermiculite-filled cores	—	—	0.53	—
200 mm, 8 to 10 kg, 1150 to 1380 kg/m^2 concrete	—	—	0.56 to 0.33	0.88
with perlite-filled cores	—	—	1.20 to 0.77	—
with vermiculite-filled cores	—	—	0.93 to 0.69	—
with molded-EPS-filled (beads) cores	—	—	0.85	—
with UF foam-filled cores	—	—	0.79	—
with molded EPS inserts in cores	—	—	0.62	—
300 mm, 16 kg, 1400 kg/m^3, concrete, 2 or 3 cores	—	—	0.46 to 0.40	—
with perlite-filled cores	—	—	1.6 to 1.1	—
with vermiculite-filled cores	—	—	1.0	—
Stone, lime, or sand	2880	10.4	—	—
Quartzitic and sandstone	2560	6.2	—	—
	2240	3.46	—	—
	1920	1.88	—	0.88
Calcitic, dolomitic, limestone, marble, and granite	2880	4.33	—	—
	2560	3.17	—	—
	2240	2.31	—	—
	1920	1.59	—	0.88
	1600	1.15	—	—
Gypsum partition tile				
75 by 300 by 760 mm, solid	—	—	0.222	0.79
4 cells	—	—	0.238	—
100 by 300 by 760 mm, 3 cells	—	—	0.294	—
Limestone	2400	0.57	—	0.84
	2600	0.93	—	0.84
Concretes[i]				
Sand and gravel or stone aggregate concretes	2400	1.4 to 2.9	—	—
(concretes with >50% quartz or quartzite	2240	1.3 to 2.6	—	0.80 to 1.00
sand have conductivities in higher end of range)	2080	1.0 to 1.9	—	—
Low-mass aggregate or limestone concretes	1920	0.9 to 1.3	—	—
expanded shale, clay, or slate; expanded slags; cinders;	1600	0.68 to 0.89	—	0.84
	1280	0.48 to 0.59	—	0.84
pumice (with density up to 1600 kg/m^3); scoria (sanded	960	0.30 to 0.36	—	—
concretes have conductivities in higher end of range)	640	0.18	—	—
Gypsum/fiber concrete (87.5% gypsum, 12.5% wood chips)	800	0.24	—	0.84
Cement/lime, mortar, and stucco	1920	1.40	—	—
	1600	0.97	—	—

Table 11.7 Building and Insulating Materials: Design Values[a]
[2017F, Ch 26, Tbl 1] ***(Continued)***

Description	Density, kg/m^3	Conductivity[b] k, $W/(m \cdot K)$	Resistance R, $(m^2 \cdot K)/W$	Specific Heat c_p, $kJ/(kg \cdot K)$
	1280	0.65	—	—
Perlite, vermiculite, and polystyrene beads	800	0.26 to 0.27	—	—
	640	0.20 to 0.22	—	0.63 to 0.96
	480	0.16	—	—
	320	0.12	—	—
Foam concretes	1920	0.75	—	—
	1600	0.60	—	—
	1280	0.44	—	—
	1120	0.36	—	—
Foam concretes and cellular concretes	960	0.30	—	—
	640	0.20	—	—
	320	0.12	—	—
Aerated concrete (oven-dried)	430 to 800	0.20	—	0.84
Polystyrene concrete (oven-dried)	255 to 800	0.37	—	0.84
Polymer concrete	1950	1.64	—	—
	2200	1.03	—	—
Polymer cement	1870	0.78	—	—
Slag concrete	960	0.22	—	—
	1280	0.32	—	—
	1600	0.43	—	—
	2000	1.23	—	—
Woods (12% moisture content)[j]				
Hardwoods	—	—	—	1.63[k]
Oak	660 to 750	0.16 to 0.18	—	—
Birch	680 to 725	0.17 to 0.18	—	—
Maple	635 to 700	0.16 to 0.17	—	—
Ash	615 to 670	0.15 to 0.16	—	—
Softwoods	—	—	—	1.63[k]
Southern pine	570 to 660	0.14 to 0.16	—	—
Southern yellow pine	500	0.13	—	—
Eastern white pine	400	0.10	—	—
Douglas fir/larch	535 to 580	0.14 to 0.15	—	—
Southern cypress	500 to 515	0.13	—	—
Hem/fir, spruce/pine/fir	390 to 500	0.11 to 0.13	—	—
Spruce	400	0.09	—	—
Western red cedar	350	0.09	—	—
West coast woods, cedars	350 to 500	0.10 to 0.13	—	—
Eastern white cedar	360	0.10	—	—
California redwood	390 to 450	0.11 to 0.12	—	—
Pine (oven-dried)	370	0.092	—	1.88
Spruce (oven-dried)	395	0.10	—	1.88

Notes for Table 11.7

[a]Values are for mean temperature of 24°C. Representative values for dry materials are intended as design (not specification) values for materials in normal use. Thermal values of insulating materials may differ from design values depending on in-situ properties (e.g., density and moisture content, orientation, etc.) and manufacturing variability. For properties of specific product, use values supplied by manufacturer or unbiased tests.

[b]Symbol λ also used to represent thermal conductivity.

[c]Does not include paper backing and facing, if any. Where insulation forms boundary (reflective or otherwise) of airspace, see 2017F, Ch 26, Tbls 2 and 3 for insulating value of airspace with appropriate effective emittance and temperature conditions of space.

[d]Conductivity varies with fiber diameter (see Chapter 25 of the 2017 *ASHRAE Handbook—Fundamentals*). Batt, blanket, and loose-fill mineral fiber insulations are manufactured to achieve specified R-values, the most common of which are listed in the table. Because of differences in manufacturing processes and materials, the product thicknesses, densities, and thermal conductivities vary over considerable ranges for a specified R-value.

[e]Insulating values of acoustical tile vary, depending on density of board and on type, size, and depth of perforations.

[f]Values for fully grouted block may be approximated using values for concrete with similar unit density.

[g]Values for concrete block and concrete are at moisture contents representative of normal use.

[h]Values for metal or vinyl siding applied over flat surfaces vary widely, depending on ventilation of the airspace beneath the siding; whether airspace is reflective or nonreflective; and on thickness, type, and application of insulating backing-board used. Values are averages for use as design guides, and were obtained from several guarded hot box tests (ASTM Standard C1363) on hollow-backed types and types made using backing of wood fiber, foamed plastic, and glass fiber. Departures of ±50% or more from these values may occur.

[i]Vinyl specific heat = 1.0 kJ/(kg·K).

[j]See Adams (1971), MacLean (1941), and Wilkes (1979). Conductivity values listed are for heat transfer across the grain. Thermal conductivity of wood varies linearly with density, and density ranges listed are those normally found for wood species given. If density of wood species is not known, use mean conductivity value. For extrapolation to other moisture contents, the following empirical equation developed by Wilkes (1979) may be used:

$$k = 0.1791 + \frac{(1.874 \times 10^{-2} + 5.753 \times 10^{-4} M)\rho}{1 + 0.01M}$$

where ρ is density of moist wood in kg/m**3**, and M is moisture content in percent.

[k]From Wilkes (1979), an empirical equation for specific heat of moist wood at 24°C is as follows:

$$c_p = \frac{(0.299 + 0.01M)}{(1 + 0.01M)} + \Delta c_p$$

where Δc_p accounts for heat of sorption and is denoted by

$$\Delta c_p = M(1.921 \times 10^{-3} - 3.168 \times 10^{-5} M)$$

where M is moisture content in percent by mass.

Cooling Load Temperature Differences (CLTDs)

Table 11.8 CLTDs for Flat Roofs—40°N Latitude, July

Roof No.	Solar time, h											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	0	–1	–2	–3	–3	–3	0	7	16	25	33	41
2	1	0	–1	–2	–3	–3	–2	2	9	18	27	34
3	7	4	3	1	0	–1	0	3	7	13	19	26
4	9	6	4	2	1	–1	–2	–2	0	4	9	16
5	12	9	7	4	3	2	1	1	3	7	12	17
8	16	13	12	9	8	7	6	6	7	9	12	16
9	18	14	12	9	7	5	3	2	2	4	7	11
10	21	18	15	13	11	8	7	6	5	6	7	9
13	19	17	16	14	12	11	10	9	9	9	11	13
14	19	18	17	15	14	13	12	11	11	11	12	13

Roof No.	Solar time, h											
	13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
1	46	49	49	46	41	33	24	14	8	5	3	1
2	41	46	48	47	44	39	31	22	14	8	5	3
3	32	37	40	41	41	37	33	27	21	17	13	9
4	23	30	36	41	43	43	41	37	31	25	19	13
5	23	28	33	37	38	38	36	33	28	23	19	15
8	19	23	27	29	31	32	31	29	27	24	21	18
9	15	20	25	29	33	35	36	35	32	29	25	21
10	13	17	21	24	28	31	32	32	31	29	26	23
13	16	18	21	23	26	27	27	27	26	24	22	21
14	16	18	20	22	23	24	25	25	24	23	22	21

CAUTION: Approximate data—Use for preliminary computations only. Also, see notes on next page.

Notes for CLTD Data for Flat Roofs

1. Data apply directly to (1) dark surface, (2) indoor temperature is 25.5°C, (3) outdoor maximum temperature of 35°C with mean temperature of 29.4°C and daily range of 11.6°C, (4) solar radiation typical of clear day on 21st day of month, (5) outside surface film resistance of 0.059 $m^2 \cdot K/W$, and (6) inside surface resistance of 0.121 $m^2 \cdot K/W$.
2. Adjustments to design temperatures

$$\text{Corr. CLTD} = \text{CLTD} + (25.5 - t_r) + (t_m - 25.5) \tag{11.5}$$

where t_r = inside temperature and t_m = mean outdoor temperature, or t_m = maximum outdoor temperature − (daily range)/2.

No adjustment recommended for color or for ventilation of air space above a ceiling.

For design purposes, the data suffice for plus or minus 2 weeks from the 21st day of given month.

Table 11.9 Roof Classifications for Use with CLTD Tables for Flat Roofs

Mass Location	Suspended Ceiling	R, $m^2 \cdot K/W$	Wood 25 mm	50 mm Heavy Concrete	Steel Deck	Attic Ceiling Comb.
Mass inside insul.	Without	0 to 1.76	*	2	*	*
		1.76 to 3.52	*	4	*	*
		3.52 to 4.40	*	5	*	*
	With	0 to 0.88	*	5	*	*
		0.88 to 1.76	*	8	*	*
		1.76 to 3.52	*	13	*	*
		3.52 to 4.40	*	14	*	*
Mass evenly placed	Without	0 to 0.88	1	2	1	1
		0.88 to 2.64	2	*	1	2
		2.64 to 4.40	4	*	2	2
	With	0 to 0.88	*	3	1	*
		0.88 to 1.76	4	*	1	*
		1.76 to 2.64	5	*	2	
		2.64 to 3.52	9	*	2	*
		3.52 to 4.40	10	*	4	*
Mass outside insul.	Without	0 to 0.88	*	2	*	*
		0.88 to 1.76	*	3	*	*
		1.76 to 2.64	*	4	*	*
		2.64 to 4.40	*	5	*	*
	With	0 to 1.76	*	3	*	*
		1.76 to 2.64	*	4	*	*
		2.64 to 3.52	*	5	*	*

*Denotes roof that is not possible with the chosen parameters

Table 11.10 CLTDs for Sunlit Walls—40° N Latitude, July

Solar time, h

Low Mass, Low R-Value Wall (No. 1)

Wall Facing	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
N	–1	4	6	6	7	9	12	14	15	16	16	16	16	15	9	6	4
NE	1	13	23	26	24	19	16	15	16	16	16	15	13	11	8	6	4
E	1	16	28	34	36	33	27	20	17	17	17	16	14	11	8	6	4
SE	0	8	18	26	31	32	31	27	22	18	17	16	14	11	8	6	4
S	–1	0	2	6	12	18	24	28	29	28	24	19	15	11	8	6	4
SW	–1	0	2	4	7	9	14	22	29	36	39	38	34	25	13	7	4
W	–1	1	2	4	7	9	12	15	23	33	41	44	44	34	18	9	5
NW	–1	0	2	4	7	9	12	14	16	21	28	34	36	31	16	8	5

Low Mass, Medium R-Value Wall (No. 4)

Wall Facing	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
N	0	0	1	2	3	4	6	7	9	11	12	13	14	15	15	14	12
NE	0	0	2	7	12	16	18	18	18	17	17	17	16	16	14	13	11
E	1	1	3	8	15	21	25	27	26	24	22	21	19	18	16	14	12
SE	1	0	1	4	9	15	20	24	26	26	24	23	21	19	17	14	12
S	1	0	–1	0	1	3	7	11	16	19	23	24	23	22	19	17	13
SW	1	0	0	0	1	3	4	7	10	15	20	26	29	32	32	28	23
W	1	1	0	1	1	3	4	6	8	12	17	22	28	33	36	33	28
NW	1	0	0	0	1	2	4	6	8	11	13	17	21	25	27	27	23

Low Mass, High R-Value Wall (No. 2)

Wall Facing	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
N	–1	–1	2	4	5	6	8	10	12	13	14	15	16	16	15	12	9
NE	–1	1	7	14	20	22	21	18	17	16	16	16	16	14	13	10	8
E	–1	1	8	18	26	31	32	29	24	21	19	18	17	15	13	11	8
SE	–1	0	4	11	18	24	28	29	28	25	22	19	17	16	13	11	8
S	–1	–1	–1	1	4	8	13	18	23	26	27	26	22	18	15	12	8
SW	–1	–1	0	1	3	5	7	11	17	23	29	34	36	34	29	22	15
W	–1	–1	0	1	3	5	7	9	13	18	26	33	38	41	37	28	19
NW	–1	–1	–1	1	3	5	7	9	12	14	18	23	28	32	30	23	16

High Mass, Low R-Value Wall (No. 5)

Wall Facing	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
N	2	1	2	3	3	4	5	7	8	9	11	12	13	13	13	13	12
NE	2	2	4	8	11	14	15	16	16	16	16	16	16	15	14	13	12
E	2	2	4	9	14	18	22	22	22	21	21	19	19	18	16	14	13
SE	2	2	3	6	10	14	18	21	22	22	21	21	19	18	17	15	13
S	2	2	1	2	2	4	7	11	14	17	19	20	20	19	18	16	13
SW	3	3	2	2	3	3	5	7	9	14	18	22	26	27	27	24	21
W	4	3	2	2	3	4	5	6	8	11	16	21	25	29	30	28	24
NW	3	2	2	2	2	3	4	6	8	9	12	15	19	22	23	22	19

High Mass, Medium R-Value Wall (No. 11)

Wall Facing	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
N	5	4	4	4	4	4	5	6	6	7	8	8	9	10	11	11	11
NE	6	5	5	6	8	9	11	12	12	13	13	13	13	14	14	13	13
E	7	6	6	7	9	12	14	16	17	17	17	17	17	17	17	16	15
SE	7	6	6	6	8	9	12	13	15	16	17	17	17	17	17	16	15
S	6	6	5	4	4	4	6	7	9	11	13	14	15	16	16	15	14
SW	9	8	7	6	6	6	6	7	8	9	12	14	17	18	20	20	19
W	10	9	8	7	7	6	7	7	7	8	11	13	16	18	21	22	21
NW	8	7	6	6	5	5	6	6	7	7	8	10	12	14	16	17	17

High Mass, High R-Value Wall (No. 16)

Wall Facing	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
N	6	6	5	4	4	4	4	4	5	6	6	7	8	9	9	10	11
NE	7	6	6	6	6	7	8	9	11	12	12	13	13	13	14	14	13
E	8	7	6	6	7	8	11	12	14	16	17	17	17	18	18	17	17
SE	8	7	6	6	6	7	8	10	12	14	15	16	17	17	17	17	17
S	8	7	6	5	4	4	4	5	6	8	9	11	13	14	15	15	15
SW	11	10	8	7	7	6	6	6	6	7	8	10	12	15	17	18	19
W	12	11	9	8	7	7	6	6	6	7	8	9	11	14	17	19	21
NW	10	9	8	7	6	6	5	5	6	6	7	8	9	11	13	15	16

CAUTION: Approximate data–Use for preliminary computations only.

Table 11.11 Solar Cooling Load (W/m^2) for Sunlit Glass—40° N Latitude, July

Use for preliminary computations only.

Glass Facing	Solar Time, h																	
	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
N	3	79	85	88	101	110	120	126	126	123	113	98	98	113	38	19	9	3	3
NE	6	268	406	422	353	236	173	151	139	126	117	101	82	57	22	9	6	3	0
E	6	293	495	583	576	485	334	211	167	142	123	104	82	57	22	9	6	3	0
SE	3	148	299	413	473	473	413	306	198	154	129	107	85	57	22	9	6	3	0
S	0	28	54	79	129	202	268	306	302	265	198	132	98	63	25	13	6	3	0
SW	0	28	54	76	95	110	123	202	318	419	476	479	419	293	110	54	25	13	6
W	0	28	54	76	95	110	120	126	205	359	498	589	605	491	180	85	41	19	9
NW	0	28	54	76	95	110	120	126	126	158	265	381	450	410	145	69	35	16	9
Hor	0	76	217	378	532	665	759	810	816	772	684	554	394	221	91	44	22	9	6

Apply data directly to standard double strength glass with no inside shade and clear sky on 21st day of month.

Adjustments to table data:
- For design purposes, data will suffice for plus or minus 2 weeks from the 21st day of July.
- For other types of glass and internal shade, multiply values by appropriate shading coefficients.
- For externally shaded glass, use north orientation values.

Table 11.12 Shading Coefficients* for Glass without or with Interior Shading by Venetian Blinds

Type of Glass	Nominal Thickness Each Pane[a], mm	No Interior Shading		Venetian Blinds[b]	
		$h_o = 22.7$	$h_o = 17.0$	Medium	Light
Single Glass					
Single					
Clear	2.4 to 6	1.00	1.00		
Clear	6 to 13	0.94	0.95		
Clear	9.5	0.90	0.92	0.64	0.55
Clear	13	0.87	0.88		
Clear pattern	3 to 7	0.83	0.85		
Heat absorbing pattern	3	0.83	0.85		
Heat absorbing[c]	5.8 to 6.4	0.69	0.73		
Heat absorbing pattern	5.8 to 6.4	0.69	0.73	0.57	0.53
Tinted	3 to 5.6	0.69	0.73		
Heat absorbing[c]	9.5	0.60	0.64	0.54	0.52
Reflective coated glass		0.30		0.25	0.23
		0.40		0.33	0.29
		0.50		0.42	0.38
		0.60		0.50	0.44
Insulating Glass					
Double[d]					
Clear out, clear in	2.4 to 3.2	0.88	0.88	0.57	0.51
Clear out, clear in	6	0.81	0.82		
Heat absorbing out, clear in	6	0.55	0.58	0.39	0.36
Reflective coated glass		0.20		0.19	0.18
		0.30		0.27	0.26
		0.40		0.34	0.33
Triple					
Clear	6	0.71			
Clear	3	0.80			

[a]Refer to manufacturer's literature for values.
[b]For vertical blinds with opaque white and beige louvers in the tightly closed position. SC is 0.25 and 0.29 when used with glass of 0.71 to 0.80 transmittance.
[c]Refers to gray, bronze, and green tinted heat-absorbing glass.
[d]Refers to factory-fabricated units with 5, 6, or 13 mm air space or to prime windows plus storm windows.

* Note: Shading Coefficient (SC) has been superseded by solar heat gain coefficient (SHGC) including the effect of incident angle of solar radiation on the glass, and the effect of type of framing. This shading coefficient table is sufficiently accurate for the approximate cooling load calculations of this publication. For the glazing portion of single-pane clear and tinted fenestration, SC = SHGC/0.87. This does not include frame effects.

Table 11.13 Representative Rates at Which Heat and Moisture are Given Off by Human Beings in Different States of Activity [2017F, Ch 18, Tbl 1]

Degree of Activity	Location	Total Heat, W		Sensible Heat, W	Latent Heat, W	% Sensible Heat that is Radiant[b]	
		Adult Male	Adjusted, M/F[a]			Low V	High V
Seated at theater	Theater, matinee	115	95	65	30		
Seated at theater, night	Theater, night	115	105	70	35	60	27
Seated, very light work	Offices, hotels, apartments	130	115	70	45		
Moderately active office work	Offices, hotels, apartments	140	130	75	55		
Standing, light work; walking	Department store; retail store	160	130	75	55	58	38
Walking, standing	Drug store, bank	160	145	75	70		
Sedentary work	Restaurant[c]	145	160	80	80		
Light bench work	Factory	235	220	80	140		
Moderate dancing	Dance hall	265	250	90	160	49	35
Walking 4.8 km/h; light machine work	Factory	295	295	110	185		
Bowling[d]	Bowling alley	440	425	170	255		
Heavy work	Factory	440	425	170	255	54	19
Heavy machine work; lifting	Factory	470	470	185	285		
Athletics	Gymnasium	585	525	210	315		

Notes:
1. Tabulated values are based on 24°C room dry-bulb temperature. For 27°C room dry bulb, total heat remains the same, but sensible heat values should be decreased by approximately 20%, and latent heat values increased accordingly.
2. Also see 2017F, Ch 9, Tbl 4 for additional rates of metabolic heat generation.
3. All values are rounded to nearest 5 W.

[a] Adjusted heat gain is based on normal percentage of men, women, and children for the application listed, and assumes that gain from an adult female is 85% of that for an adult male, and gain from a child is 75% of that for an adult male.
[b] Values approximated from data in 2017F, Ch 9, Tbl 6, where V is air velocity.
[c] Adjusted heat gain includes 18 W for food per individual (9 W sensible and 9 W latent).
[d] Figure one person per alley actually bowling, and all others as sitting (117 W) or standing or walking slowly (231 W).

Heat Gain from Lighting

The energy absorbed by the structure and contents contributes to space cooling load only after a time lag, some still reradiating after the heat sources have been switched off. This may make load lower than instantaneous heat gain, thus affecting the peak load.

Instantaneous rate of heat gain from lights, q_{el} kW:

$$q_{el} = WF_{ul}F_{sa} \tag{11.6}$$

where

W	=	total lights wattage installed
F_{ul}	=	lighting use factor (proportion in use)
F_{sa}	=	lighting special allowance factor
3.41	=	conversion factor

The **total light wattage** is obtained from the ratings of all lamps installed, both for general illumination and for display use. Ballasts are not included, but are addressed by a separate factor. Wattages of magnetic ballasts are significant; the energy consumption of high-efficiency electronic ballasts might be insignificant compared to that of the lamps.

The **lighting use factor** is the ratio of wattage in use, for the conditions under which the load estimate is being made, to total installed wattage. For commercial applications such as stores, the use factor is generally 1.0.

The **special allowance factor** is the ratio of the lighting fixtures' power consumption, including lamps and ballast, to the nominal power consumption of the lamps. For incandescent lights, this factor is 1. For fluorescent lights, it accounts for power consumed by the ballast as well as the ballast's effect on lamp power consumption. The special allowance factor can be less than 1 for electronic ballasts that lower electricity consumption below the lamp's rated power consumption. Use manufacturers' values for system (lamps + ballast) power, when available.

For high-intensity-discharge lamps (e.g. metal halide, mercury vapor, high- and low-pressure sodium vapor lamps), the actual lighting system power consumption should be available from the manufacturer of the fixture or ballast. Ballasts available for metal halide and high pressure sodium vapor lamps may have special allowance factors from about 1.3 (for low-wattage lamps) down to 1.1 (for high-wattage lamps).

An alternative procedure is to estimate the lighting heat gain on a per square foot basis. Such an approach may be required when final lighting plans are not available. Table 11.14 shows the maximum lighting power density (LPD) (lighting heat gain per square metre) allowed by ASHRAE Standard 90.1-2010 for a range of space types.

Table 11.14 Lighting Power Densities Using Space-by-Space Method
[2017F, Ch 18, Tbl 2]

Common Space Types*	LPD, W/m^2
Atrium	
≤12.2 m high	1.1/m total height
>12.2 m high	4.3 + 0.7/m total height
Audience Seating Area	
In auditorium	6.8
In convention center	8.9
In gymnasium	7.1
In motion picture theater	12.3
In penitentiary	3.1
In performing arts theater	26.2
In religious building	16.5
In sports arena	4.7
All other audience seating areas	4.7
Banking Activity Area	11.9
Breakroom (*See* Lounge/Breakroom)	
Classroom/Lecture Hall/Training Room	
In penitentiary	14.5
All other classrooms/lecture halls/training rooms	13.4
Conference/Meeting/Multipurpose Room	13.3
Confinement Cells	8.8
Copy/Print Room	7.8
Corridor[b]	
In facility for visually impaired (and not used primarily by staff)[c]	9.9
In hospital	10.7
In manufacturing facility	4.4
All other corridors	7.1
Courtroom	18.6
Computer Room	18.4
Dining Area	
In penitentiary	10.4
In facility for visually impaired (and not used primarily by staff)[c]	28.5
In bar/lounge or leisure dining	11.6
In cafeteria or fast food dining	7.0
In family dining	9.6
All other dining areas	7.0

Common Space Types[a]	LPD, W/m^2
Electrical/Mechanical Room[f]	4.6
Emergency Vehicle Garage	6.1
Food Preparation Area	13.1
Guest Room	9.8
Laboratory	
In or as classroom	15.5
All other laboratories	19.5
Laundry/Washing Area	6.5
Loading Dock, Interior	5.1
Lobby	
In facility for the visually impaired (and not used primarily by staff)[c]	19.4
For elevator	7.0
In hotel	11.5
In motion picture theater	6.4
In performing arts theater	21.6
All other lobbies	9.7
Locker Room	8.1
Lounge/Breakroom	
In health care facility	10.0
All other lounges/breakrooms	7.9
Office	
Enclosed	12.0
Open plan	10.6
Parking Area, Interior	2.1
Pharmacy Area	18.1
Restroom	
In facility for the visually impaired (and not used primarily by staff)[c]	13.1
All other restrooms	10.6
Sales Area[d]	15.5
Seating Area, General	5.9
Stairway	
Space containing stairway determines LPD and control requirements for stairway.	
Stairwell	7.4
Storage Room	
<4.65 m^2	13.3
All other storage rooms	6.8
Vehicular Maintenance Area	7.3
Workshop	17.2

Table 11.14 Lighting Power Densities Using Space-by-Space Method
[2017F, Ch 18, Tbl 2] **(*Continued*)**

Building-Specific Space Types*	LPD, W/m^2	Building-Specific Space Types*	LPD, W/m^2
Facility for Visually Impaired[c]		**Manufacturing Facility**	
In chapel (used primarily by residents)	23.8	In detailed manufacturing area	13.9
		In equipment room	8.0
In recreation room/common living room (and not used primarily by staff)	26.0	In extra-high-bay area (15.2 m floor-to-ceiling height)	11.3
		In high-bay area (7.6 to 15.2 m floor-to-ceiling height)	13.3
Automotive (*See* Vehicular Maintenance Area)		In low-bay area (<7.6 m floor-to-ceiling height)	12.9
Convention Center: Exhibit Space	15.7	**Museum**	
Dormitory/Living Quarters	4.2	In general exhibition area	11.4
Fire Station: Sleeping Quarters	0.22	In restoration room	11.0
Gymnasium/Fitness Center		**Performing Arts Theater, Dressing Room**	6.6
In exercise area	7.8	**Post Office, Sorting Area**	10.2
In playing area	13.0	**Religious Buildings**	
Health Care Facility		In fellowship hall	6.9
In exam/treatment room	18.0	In worship/pulpit/choir area	16.5
In imaging room	16.3	**Retail Facilities**	
In medical supply room	7.96	In dressing/fitting room	7.7
In nursery	9.5	In mall concourse	11.9
In nurses' station	7.6	**Sports Arena, Playing Area**	
In operating room	26.8	For Class I facility	39.7
In patient room	6.7	For Class II facility	25.9
In physical therapy room	9.9	For Class III facility	19.4
In recovery room	12.4	For Class IV facility	13.0
Library		**Transportation Facility**	
In reading area	11.5	In baggage/carousel area	5.7
In stacks	18.4	In an airport concourse	3.9
		At a terminal ticket counter	8.7
		Warehouse—Storage Area	
		For medium to bulky, palletized items	6.2
		For smaller, hand-carried items[e]	10.2

Source: ASHRAE Standard 90.1-2013.

[a]In cases where both a common space type and a building-specific type are listed, the building-specific space type applies.

[b]In corridors, extra lighting power density allowance is granted when corridor width is <2.4 m and is not based on room/corridor ratio (RCR).

[c]A facility for the visually impaired one that can be documented as being designed to comply with light levels in ANSI/IES RP-28 and is (or will be) licensed by local/state authorities for either senior long-term care, adult day-care, senior support, and/or people with special visual needs.

[d]For accent lighting, see section 9.6.2(b) of ASHRAE Standard 90.1-2013.

[e]Sometimes called a picking area.

[f]An additional 5.7 W/m^2 is allowed *only* if this additional lighting is controlled separately from the base allowance of 4.5 W/m^2.

Table 11.15 provides a range of design data under typical operating conditions: airflow 5 L/s·m², supply air between 15°C and 18ºC, room temperature between 22°C and 24ºC, and lighting heat input in a range from 10 to 28 W/m². For a fluorescent luminaire without lens, Figure 11.1 gives more precise data. The data should be used with judgment.

Table 11.15 Lighting Heat Gain Parameters for Typical Operating Conditions
[2017F, Ch 18, Tbl 3]

Luminaire Category	Space Fraction	Radiative Fraction	Notes
Recessed fluorescent luminaire without lens	0.64 to 0.74	0.48 to 0.68	• Use middle values in most situations • May use higher space fraction, and lower radiative fraction for luminaire with side-slot returns • May use lower values of both fractions for direct/indirect luminaire • May use higher values of both fractions for ducted returns
Recessed fluorescent luminaire with lens	0.40 to 0.50	0.61 to 0.73	• May adjust values in the same way as for recessed fluorescent luminaire without lens
Downlight compact fluorescent luminaire	0.12 to 0.24	0.95 to 1.0	• Use middle or high values if detailed features are unknown • Use low value for space fraction and high value for radiative fraction if there are large holes in luminaire's reflector
Downlight incandescent luminaire	0.70 to 0.80	0.95 to 1.0	• Use middle values if lamp type is unknown • Use low value for space fraction if standard lamp (i.e. A-lamp) is used • Use high value for space fraction if reflector lamp (i.e. BR-lamp) is used
Non-in-ceiling fluorescent luminaire	1.0	0.5 to 0.57	• Use lower value for radiative fraction for surface-mounted luminaire • Use higher value for radiative fraction for pendant luminaire

Source: Fisher and Chantrasrisalai (2006).

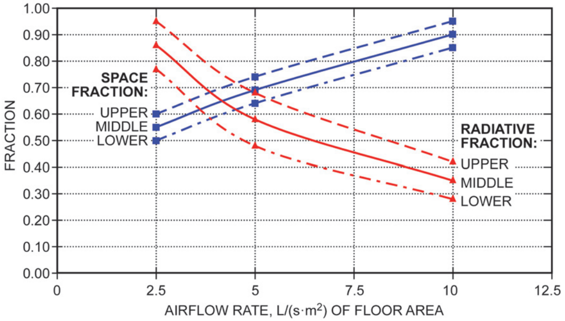


Figure 11.1 Lighting Heat Gain Parameters for Recessed Fluorescent Luminaire Without Lens
[2017F, Ch 18, Fig 3]

Heat Gain from Motors and their Loads

Instantaneous rate of heat gain from equipment operated by electric motors within a conditioned space.

$$q_{em} = (\mathrm{P}/E_M)\, F_{UM}\, F_{LM} \tag{11.7}$$

where

q_{em}	=	heat equivalent of equipment operation, kW
P	=	motor power rating, kW
E_M	=	motor efficiency, decimal fraction < 1.0
F_{UM}	=	motor use factor 1.0 or <1.0 (proportion operating)
F_{LM}	=	motor load factor 1.0 or <1.0

When motor is outside the conditioned space, but load is inside,

$$q_{em} = P\, F_{UM}\, F_{LM} \tag{11.8}$$

When motor is inside the conditioned space, but load is outside,

$$q_{em} = P\left(\frac{1.0 - E_M}{E_M}\right) F_{UM}\, F_{LM} \tag{11.9}$$

Heat output of a motor is generally proportional to motor load, within rated overload limits. Because of typically high no-load motor current, fixed losses, and other reasons, F_{LM} is generally assumed to be unity, and no adjustment should be made for underloading or overloading unless the situation is fixed and can be accurately established, and reduced-load efficiency data can be obtained from the motor manufacturer.

Unless the manufacturer's technical literature indicates otherwise, motor heat gain normally should be equally divided between radiant and convective components for the subsequent cooling load calculations.

Table 11.16 Minimum Nominal Full-Load Efficiency for 60 HZ NEMA General Purpose Electric Motors (Subtype I) Rated 600 Volts or Less (Random Wound)*
[2017F, Ch 18, Tbl 4A]

Minimum Nominal Full Load Efficiency (%) for Motors Manufactured on or after December 19, 2010						
	Open Drip-Proof Motors			Totally Enclosed Fan-Cooled Motors		
Number of Poles ⇒	2	4	6	2	4	6
Synchronous Speed (RPM) ⇒	3600	1800	1200	3600	1800	1200
Motor Kilowatts						
0.8	77.0	85.5	82.5	77.0	85.5	82.5
1.1	84.0	86.5	86.5	84.0	86.5	87.5
1.5	85.5	86.5	87.5	85.5	86.5	88.5
2.2	85.5	89.5	88.5	86.5	89.5	89.5
3.7	86.5	89.5	89.5	88.5	89.5	89.5
5.6	88.5	91.0	90.2	89.5	91.7	91.0
7.5	89.5	91.7	91.7	90.2	91.7	91.0
11.1	90.2	93.0	91.7	91.0	92.4	91.7
14.9	91.0	93.0	92.4	91.0	93.0	91.7
18.7	91.7	93.6	93.0	91.7	93.6	93.0
22.4	91.7	94.1	93.6	91.7	93.6	93.0
29.8	92.4	94.1	94.1	92.4	94.1	94.1
37.3	93.0	94.5	94.1	93.0	94.5	94.1
44.8	93.6	95.0	94.5	93.6	95.0	94.5
56.0	93.6	95.0	94.5	93.6	95.4	94.5
74.6	93.6	95.4	95.0	94.1	95.4	95.0
93.3	94.1	95.4	95.0	95.0	95.4	95.0
111.9	94.1	95.8	95.4	95.0	95.8	95.8
149.2	95.0	95.8	95.4	95.4	96.2	95.8
186.5	95.0	95.8	95.4	95.8	96.2	95.8
223.8	95.4	95.8	95.4	95.8	96.2	95.8
261.1	95.4	95.8	95.4	95.8	96.2	95.8
298.4	95.8	95.8	95.8	95.8	96.2	95.8
357.7	95.8	96.2	96.2	95.8	96.2	95.8
373.0	95.8	96.2	96.2	95.8	96.2	95.8

Source: ASHRAE/IES Standard 90.1-2013

*Nominal efficiencies established in accordance with NEMA Standard MG1. Design A and Design B are National Electric Manufacturers Association (NEMA) design class designations for fixed-frequency small and medium AC squirrel-cage induction motors.

Cooking Appliances

Heat gain: $q_s = q_{input} F_U F_R$, where F_U is the usage factor and F_R is the radiation factor.

Table 11.17 Recommended Rates of Radiant and Convective Heat Gain from Unhooded Electric Appliances During Idle (Ready-to-Cook) Conditions [2017F, Ch 18, Tbl 5A]

Appliance	Energy Rate, W		Rate of Heat Gain, W				Usage Factor F_U	Radiation Factor F_R
	Rated	Standby	Sensible Radiant	Sensible Convective	Latent	Total		
Cabinet: hot serving (large), insulated[a]	1993	352	117	234	0	352	0.18	0.33
hot serving (large), uninsulated	1993	1026	205	821	0	1026	0.51	0.20
proofing (large)[a]	5099	410	352	0	59	410	0.08	0.86
proofing (small-15 shelf)	4191	1143	0	264	879	1143	0.27	0.00
Cheesemelter[b]	2400	976	443	533	0	976	0.41	0.45
Coffee brewing urn	3810	352	59	88	205	352	0.08	0.17
Drawer warmers, 2-drawer (moist holding)[a]	1202	147	0	0	59	59	0.12	0.00
Egg cooker[b]	2380	249	65	184	0	249	0.10	0.26
Espresso machine[a]	2403	352	117	234	0	352	0.15	0.33
Food warmer: steam table (2-well-type)	1495	1026	88	176	762	1026	0.69	0.08
Freezer (small)	791	322	147	176	0	322	0.41	0.45
Fryer, countertop, open deep fat[b]	4600	431	202	229	0	431	0.09	0.47
Griddle, countertop[b]	8000	1771	848	923	0	1771	0.22	0.48
Hot dog roller[b]	1600	1240	267	973	0	1240	0.77	0.22
Hot plate: single element, high speed[b]	1100	982	314	668	0	982	0.89	0.32
Hot-food case (dry holding)[a]	9115	733	264	469	0	733	0.08	0.36
Hot-food case (moist holding)[a]	9115	967	264	528	176	967	0.11	0.27
Induction hob, countertop[b]	5000	0	0	0	0	0	0.00	0.00
Microwave oven: commercial[b]	1700	0	0	0	0	0	0	0.00
Oven: countertop conveyorized bake/finishing[b]	5000	3932	718	3214	0	3932	0.79	0.18
Panini[b]	1800	673	195	478	0	673	0.37	0.29
Popcorn popper[b]	850	115	28	87	0	115	0.14	0.24
Rapid-cook oven (quartz-halogen)[a]	12 016	0	0	0	0	0	0	0.00
Rapid-cook oven (microwave/convection)[b]	5700	1141	96	1045	0	1141	0.20	0.08
Reach-in refrigerator[a]	1407	352	88	264	0	352	0.25	0.25
Refrigerated prep table[a]	586	264	176	88	0	264	0.45	0.67
Rice cooker[b]	1550	82	14	68	0	82	0.05	0.17
Soup warmer[b]	800	390	0	53	337	390	0.49	0.00
Steamer (bun)[b]	1500	200	32	168	0	200	0.13	0.16
Steamer, countertop[b]	8300	344	0	248	96	344	0.04	0.00
Toaster: 4-slice pop up (large): cooking	1788	879	59	410	293	762	0.49	0.07
contact (vertical)[b]	2600	759	180	579	0	759	0.29	0.24
conveyor (large)	9613	3019	879	2139	0	3019	0.31	0.29
small conveyor[b]	1745	1702	358	1344	0	1702	0.98	0.21
Tortilla grill[b]	2200	1034	254	780	0	1034	0.47	0.25
Waffle iron[b]	2700	267	60	207	0	267	0.10	0.22

Sources: Swierczyna et al. (2008, 2009), with the following exceptions as noted.
[a]Swierczyna et al. (2009) only.
[b]Additions and updates from ASHRAE research project RP-1631 (Kong and Zhang 2016; Zhang et al. 2016).

Table 11.18 Recommended Rates of Radiant and Convective Heat Gain from Unhooded Electric Appliances during Cooking Conditions [2017F, Ch 18, Tbl 5B]

	Energy Rate, W		Rate of Heat Gain, W					
Appliance	**Rated**	**Cooking**	**Sensible Radiant**	**Sensible Convective**	**Latent**	**Total**	**Usage Factor F_U**	**Radiation Factor F_R**
Cheesemelter	2400	2714	443	1094	599	2136	1.13	0.16
Egg cooker	2380	1191	65	369	630	1065	0.50	0.05
Fryer, countertop, open deep fryer	4600	3818	202	492	1629	2323	0.83	0.05
Griddle, countertop	8000	3280	848	631	1277	2757	0.41	0.26
Hot dog roller	1600	1577	267	611	679	1556	0.99	0.17
Hot plate, single burner	1100	985	313	627	44	985	0.90	0.32
Induction hob, countertop	5000	653	0	318	335	653	0.13	0.00
Oven, conveyor	5000	4292	718	2454	193	3365	0.86	0.17
Microwave	1700	2363	0	934	995	1929	1.39	0.00
Rapid cook	5700	2310	96	1234	771	2102	0.41	0.04
Panini grill	1800	1374	195	718	150	1062	0.76	0.14
Popcorn popper	850	576	28	236	192	457	0.68	0.05
Rice cooker	1550	1159	14	95	44	153	0.75	0.01
Soup warmer	800	842	0	85	716	801	1.05	0.00
Steamer (bun)	1500	791	32	240	511	783	0.53	0.04
Steamer, countertop	8300	7731	0	499	6934	7433	0.93	0.00
Toaster, conveyor	1745	1705	358	974	373	1705	0.98	0.21
Vertical	2600	1841	180	715	322	1218	0.71	0.10
Tortilla grill	2200	2194	254	1267	673	2194	1.00	0.12
Waffle maker	2700	1180	60	357	559	975	0.44	0.05

Source: ASHRAE research project RP-1631 (Zhang et al. 2015).

Table 11.19 Recommended Rates of Radiant Heat Gain from Hooded Electric Appliances During Idle (Ready-to-Cook) Conditions [2017F, Ch 18, Tbl 5C]

	Energy Rate, W		Rate of Heat Gain, W		
Appliance	**Rated**	**Standby**	**Sensible Radiant**	**Usage Factor F_U**	**Radiation Factor F_R**
Broiler: underfired 900 mm	10 814	9 056	3165	0.84	0.35
Cheesemelter*	3 605	3 488	1348	0.97	0.39
Fryer, kettle	29 014	528	147	0.02	0.28
Open deep-fat, 1-vat	14 008	821	293	0.06	0.36
Pressure	13 511	791	147	0.06	0.19
Griddle, double-sided 900 mm (clamshell down)*	21 218	2 022	410	0.10	0.20
(Clamshell up)*	21 218	3 370	1055	0.16	0.31
Flat 900 mm	17 115	3 370	1319	0.20	0.39
Small 900 mm*	8 997	1 788	791	0.20	0.44
Induction cooktop*	21 013	0	0	0.00	0.00
Induction wok*	3 488	0	0	0.00	0.00
Oven, combi: combi-mode*	16 411	1 612	234	0.10	0.15
Combi: convection mode	16 412	1 612	410	0.10	0.25
Oven, convection full-size	12 103	1 964	440	0.16	0.22
Convection half-size*	5 510	1 084	147	0.20	0.14
Pasta cooker*	22 010	2 491	0	0.11	0.00
Range top, top off/oven on*	4 865	1 172	293	0.24	0.25
3 elements on/oven off	15 005	4 513	1846	0.30	0.41
6 elements on/oven off	15 005	9 730	4074	0.65	0.42
6 elements on/oven on	19 870	10 668	4250	0.54	0.40
Range, hot-top	15 826	15 035	3458	0.95	0.23
Rotisserie*	11 107	4 044	1319	0.36	0.33
Salamander*	7 004	6 829	2051	0.97	0.30
Steam kettle, large (225 L), simmer lid down*	32 414	762	29	0.02	0.04
small (150 L), simmer lid down*	21 599	528	88	0.02	0.17
Steamer, compartment, atmospheric*	9 789	4 484	59	0.46	0.01
Tilting skillet/braising pan	9 642	1 553	0	0.16	0.00

*Items with an asterisk appear only in Swierczyna et al. (2009); all others appear in both Swierczyna et al. (2008) and (2009).

Table 11.20 Recommended Rates of Radiant Heat Gain from Hooded Gas Appliances during Idle (Ready-to-Cook) Conditions [2017F, Ch 18, Tbl 5D]

Appliance	Standby Energy Rate, W		Rate of Heat Sensible Gain, W	Usage Factor F_U	Radiation Factor F_R
Broiler: batch*	27 842	20 280	2374	0.73	0.12
Chain (conveyor)	38 685	28 340	3869	0.73	0.14
Overfired (upright)*	29 307	25 761	733	0.88	0.03
Underfired 900 mm	28 135	21 658	2638	0.77	0.12
Fryer: doughnut	12 895	3634	850	0.28	0.23
Open deep-fat, 1 vat	23 446	1377	322	0.06	0.23
Pressure	23 446	2638	234	0.11	0.09
Griddle: double sided 900 mm, clamshell down*	31 710	2345	528	0.07	0.23
Clamshell up*	31 710	4308	1436	0.14	0.33
Flat 900 mm	26 376	5979	1084	0.23	0.18
Oven: combi: combi-mode*	22 185	1758	117	0.08	0.07
Convection mode	22 185	1700	293	0.08	0.17
Convection, full-size	12 895	3488	293	0.27	0.08
Conveyor (pizza)	49 822	20 017	2286	0.40	0.11
Deck	30 772	6008	1026	0.20	0.17
Rack mini-rotating*	16 500	1319	322	0.08	0.24
Pasta cooker*	23 446	6946	0	0.30	0.00
Range top: top off/oven on*	7327	2169	586	0.30	0.27
3 burners on/oven off	35 169	17 614	2081	0.50	0.12
6 burners on/oven off	35 169	35 403	3370	1.01	0.10
6 burners on/oven on	42 495	36 018	3986	0.85	0.11
Range: wok*	29 014	25 614	1524	0.88	0.06
Rethermalizer*	26 376	6829	3370	0.26	0.49
Rice cooker*	10 257	147	88	0.01	0.60
Salamander*	10 257	9759	1553	0.95	0.16
Steam kettle: large (225 L) simmer lid down*	42 495	1583	0	0.04	0.00
Small (38 L) simmer lid down*	15 240	967	88	0.06	0.09
Medium (150 L) simmer lid down	29 307	1260	0	0.04	0.00
Steamer: compartment: atmospheric*	7620	2432	0	0.32	0.00
Tilting skillet/braising pan	30 479	3048	117	0.10	0.04

*Items with an asterisk appear only in Swierczyna et al. (2009); all others appear in both Swierczyna et al. (2008) and (2009).

Table 11.21 Recommended Rates of Radiant Heat Gain from Hooded Solid-Fuel Appliances during Idle (Ready-to-Cook) Conditions [2017F, Ch 18, Tbl 5E]

Appliance	Rated	Standby Energy Rate, W	Rate of Sensible Heat Gain, W	Usage Factor F_U	Radiation Factor F_R
Broiler: solid fuel: charcoal	18 kg	12 309	1817	N/A	0.15
Broiler: solid fuel: wood (mesquite)	18 kg	14 536	2051	N/A	0.14

Source: Swierczyna et al. (2008).

Table 11.22 Recommended Rates of Radiant and Convective Heat Gain from Warewashing Equipment during Idle (Standby) or Washing Conditions [2017F, Ch 18, Tbl 5F]

	Energy Rate, W		Rate of Heat Gain, W						
			Unhooded				Hooded		
Appliance	Rated	Standby/ Washing	Sensible Radiant	Sensible Convective	Latent	Total	Sensible Radiant	Usage Factor F_U	Radiation Factor F_R
Dishwasher: conveyor type, hot-water sanitizing, washing	13,712	N/A	0	3,545	13,771	17,316	0	N/A	0.00
Standby	13,712	1,670	0	469	1,201	1,670	0	0.12	0.00
Dishwasher: conveyor type, chemical sanitizing, washing	13,712	12,775	0	3,252	10,372	13,624	0	0.93	0.00
Standby	13,712	1,670	0	469	1,201	1,670	0	0.12	0.00
Dishwasher: door type, hot-water sanitizing, washing	17,609	5,420	0	2,227	7,384	9,610	0	0.31	0.00
With heat recovery and vapor reduction	15,207	7,940	0	1,699	3,838	5,538	0	0.52	0.00
Standby	5,391	352	0	668	1,222	1,890	0	0.35	0.00
Dishwasher: door type, chemical sanitizing, washing	8,790	4,571	0	1,143	3,868	5,010	0	0.52	0.00
Standby	5,391	352	0	264	88	352	0	0.07	0.00
Dishwasher: door type, chemical sanitizing, dump and fill, washing	1,787	879	0	850	1,231	2,080	0	0.49	0.00
Standby	1,787	879	0	0	0	0	0	0.49	0.00
Pot and pan washer: door type, hot-water sanitizing, washing	15,587	10,665	0	1,758	6,885	8,643	0	0.68	0.00
With heat recovery and vapor reduction	15,587	10,314	0	1,611	5,567	7,178	0	0.66	0.00
Dishwasher: under-counter type, hot-water sanitizing, washing	8,350	2,227	234	938	2,022	3,194	800	0.27	0.11
With heat recovery and vapor reduction	7,794	6,680	0	586	322	908	0	0.86	0.00
Standby	7,794	498	234	146	117	498	800	0.06	0.47
Dishwasher: under-counter type, chemical sanitizing, washing	8,350	2,022	0	645	1,436	2,080	0	0.24	0.00
Standby	7,794	498	0	146	117	264	0	0.06	0.00
Booster heater	38,090	0	146	0	0	0	500	0	N/A

Sources: PG&E (2010-2016), Swierczyna et al. (2008, 2009).

Hospital and Laboratory Equipment

Heat gain varies significantly. In a laboratory, heat gain ranges from 50 to 220 W/m^2. Medical equipment is highly varied in type and application. Table 11.23 is relevant for portable and bench-type equipment. For large equipment, such as MRI, obtain heat gain from the manufacturer.

Table 11.23 Recommended Heat Gain from Typical Medical Equipment
[2017F, Ch 18, Tbl 6]

Equipment	Nameplate, W	Peak, W	Average, W
Anesthesia system	250	177	166
Blanket warmer	500	504	221
Blood pressure meter	180	33	29
Blood warmer	360	204	114
ECG/RESP	1440	54	50
Electrosurgery	1000	147	109
Endoscope	1688	605	596
Harmonical scalpel	230	60	59
Hysteroscopic pump	180	35	34
Laser sonics	1200	256	229
Optical microscope	330	65	63
Pulse oximeter	72	21	20
Stress treadmill	N/A	198	173
Ultrasound system	1800	1063	1050
Vacuum suction	621	337	302
X-ray system	968		82
	1725	534	480
	2070		18

Source: Hosni et al. (1999)

Table 11.24 Recommended Heat Gain from Typical Laboratory Equipment
[2017F, Ch 18, Tbl 7]

Equipment	Nameplate, W	Peak, W	Average, W
Analytical balance	7	7	7
Centrifuge	138	89	87
	288	136	132
	5500	1176	730
Electrochemical analyzer	50	45	44
	100	85	84
Flame photometer	180	107	105
Fluorescent microscope	150	144	143
	200	205	178
Function generator	58	29	29
Incubator	515	461	451
	600	479	264
	3125	1335	1222
Orbital shaker	100	16	16
Oscilloscope	72	38	38
	345	99	97
Rotary evaporator	75	74	73
	94	29	28
Spectronics	36	31	31
Spectrophotometer	575	106	104
	200	122	121
	N/A	127	125
Spectro fluorometer	340	405	395
Thermocycler	1840	965	641
	N/A	233	198
Tissue culture	475	132	46
	2346	1178	1146

Source: Hosni et al. (1999).

Heat Gain from Office Equipment

Table 11.25 Recommended Heat Gain for Typical Desktop Computers
[2017F, Ch 18, Tbl 8A]

Description	Nameplate Power,[a] W	Peak Heat Gain,[b, d] W
Manufacturer 1		
3.0 GHz processor, 4 GB RAM, *n* = 1	NA	83
3.3 GHz processor, 8 GB RAM, *n* = 8	NA	50
3.5 GHz processor, 8 GB RAM, *n* = 2	NA	42
3.6 GHz processor, 16 GB RAM, *n* = 2	NA	66
3.3 GHz processor, 16 GB RAM, *n* = 2	NA	52
4.0 GHz processor, 16 GB RAM, *n* = 1	NA	83
3.3 GHz processor, 8 GB RAM, *n* = 1	NA	84
3.7 GHz processor, 32 GB RAM, *n* = 1	750	116
	NA	102
3.5 GHz processor, 16 GB RAM, *n* = 3[c]	550	144
	NA	93
Manufacturer 2		
3.6 GHz processor, 32 GB RAM, *n* = 8	NA	80
3.6 GHz processor, 16 GB RAM, *n* = 1	NA	78
3.4 GHz processor, 32 GB RAM, *n* = 1	NA	72
3.4 GHz processor, 24 GB RAM, *n* = 1	NA	86
3.50 GHz processor, 4 GB RAM, *n* = 1	NA	26
3.3 GHz processor, 8 GB RAM, *n* = 1	NA	78
3.20 GHz processor, 8 GB RAM, *n* = 1	NA	61
3.20 GHz processor, 4 GB RAM, *n* = 1	NA	44
2.93 GHz processor, 16 GB RAM, *n* = 1	NA	151
2.67 GHz processor, 8 GB RAM, *n* = 1	NA	137
Average 15-min peak power consumption (range)	82 (26-151)	

Source: Bach and Sarfraz (2017)
n = number of tested equipment of same configuration.
[a]Nameplate for desktop computer is present on its power supply, which is mounted inside desktop, hence not accessible for most computers, where NA = not available.
[b]For equipment peak heat gain value, highest 15-min interval of recorded data is listed in tables.
[c]For tested equipment with same configuration, increasing power supply size does not increase average power consumption.
[d]Approximately 90% convective heat gain and 10% radiative heat gain.

Table 11.26 Recommended Heat Gain for Typical Laptops and Laptop Docking Station
[2017F, Ch 18, Tbl 8B]

Equipment	Description	Nameplate Power,[a] W	Peak Heat Gain,[b, c] W
Laptop computer	Manufacturer 1, 2.6 GHz processor, 8 GB RAM, n = 1	NA	46
	Manufacturer 2, 2.4 GHz processor, 4 GB RAM, n = 1	NA	59
Average 15-min peak power consumption (range)		53 (46-59)	
Laptop with docking station	Manufacturer 1, 2.7 GHz processor, 8 GB RAM, n = 1	NA	38
	1.6 GHz processor, 8 GB RAM, n = 2	NA	45
	2.0 GHz processor, 8 GB RAM, n = 1	NA	50
	2.6 GHz processor, 4 GB RAM, n = 1	NA	51
	2.4 GHz processor, 8 GB RAM, n = 1	NA	40
	2.6 GHz processor, 8 GB RAM, n = 1	NA	35
	2.7 GHz processor, 8 GB RAM, n = 1	NA	59
	3.0 GHz processor, 8 GB RAM, n = 3	NA	70
	2.9 GHz processor, 32 GB RAM, n = 3	NA	58
	3.0 GHz processor, 32 GB RAM, n = 1	NA	128
	3.7 GHz processor, 32 GB RAM, n = 1	NA	63
	3.1 GHz processor, 32 GB RAM, n = 1	NA	89
Average 15-min peak power consumption (range)		61 (26-151)	

Source: Bach and Sarfraz (2017)
n = number of tested equipment of same configuration.
[a]Voltage and amperage information for laptop computer and laptop docking station is available on power supply nameplates; however, nameplate does not provide information on power consumption, where NA = not available.
[b]For equipment peak heat gain value, the highest 15-min interval of recorded data is listed in tables.
[c]Approximately 75% convective heat gain and 25% radiative heat gain.

Table 11.27 Recommended Heat Gain for Typical Tablet PC
[2017F, Ch 18, Tbl 8C]

Description	Nameplate Power,[a] W	Peak Heat Gain,[b] W
1.7 GHz processor, 4 GB RAM, n = 1	NA	42
2.2 GHz processor, 16 GB RAM, n = 1	NA	40
2.3 GHz processor, 8 GB RAM, n = 1	NA	30
2.5 GHz processor, 8 GB RAM, n = 1	NA	31
Average 15-min peak power consumption (range)	36 (31-42)	

Source: Bach and Sarfraz (2017)
n = number of tested equipment of same configuration.
[a]Voltage and amperage information for tablet PC is available on power supply nameplate; however, nameplate does not provide information on power consumption, where NA = not available.
[b]For equipment peak heat gain value, highest 15-min interval of recorded data is listed in tables.

Table 11.28 Recommended Heat Gain for Typical Monitors
[2017F, Ch 18, Tbl 8D]

Description[a]	Nameplate Power, W	Peak Heat Gain,[b, c] W
Manufacturer 1		
1397 mm LED flat screen, *n* = 1 (excluded from average because atypical size)	240	50
686 mm LED flat screen, *n* = 2	40	26
546 mm LED flat screen, *n* = 2	29	25
Manufacturer 2		
1270 mm 3D LED flat screen, *n* = 1 (excluded from average because atypical size)	94	49
Manufacturer 3		
864 mm LCD curved screen, *n* = 1 (excluded from average because atypical size and curved)	130	48
584 mm LED flat screen, *n* = 3	50	17
584 mm LED flat screen, *n* = 1	38	21
584 mm LED flat screen, *n* = 1	38	14
Manufacturer 4		
610 mm LED flat screen, *n* = 1	42	25
Manufacturer 5		
600 mm LED flat screen, *n* = 1	26	17
546 mm LED flat screen, *n* = 1	29	22
Manufacturer 6		
546 mm LED flat screen, *n* = 1	28	24
Average 15-min peak power consumption (range)	21 (14-26)	

Source: Bach and Sarfraz (2017)
n = number of tested equipment of same configuration.
[a]Screens with atypical size and shape are excluded for calculating average 15-min peak power consumption.
[b]For equipment peak heat gain value, highest 15-min interval of recorded data is listed in tables.
[c]Approximately 60% convective heat gain and 40% radiative heat gain.

Table 11.29 Recommended Heat Gain for Miscellaneous Equipment
[2017F, Ch 18, Tbl 10]

Equipment	Nameplate Power,[a] W	Peak Heat Gain,[b] W
Vending machine		
Drinks, 280 to 400 items	NA	940
Snacks	NA	54
Food (e.g., for sandwiches)	NA	465
Thermal binding machine, 2 single documents up to 340 pages	350	28.5
Projector, resolution 1024 × 768	340	308
Paper shredder, up to 28 sheets	1415	265
Electric stapler, up to 45 sheets	NA	1.5
Speakers	220	15
Temperature-controlled electronics soldering station	95	16
Cell phone charger	NA	5
Battery charger		
40 V	NA	19
AA	NA	5.5
Microwave oven, 25 to 34 L	1000 to 1550	713 to 822
Coffee maker		
Single cup	1400	385
Up to 12 cups	950	780
With grinder	1350	376
Coffee grinder, up to 12 cups	NA	73
Tea kettle, up to 6 cups	1200	1200
Dorm fridge, 88 L	NA	57
Freezer, 510 L	130	125
Fridge, 510 L	NA	387 to 430
Ice maker and dispenser, 9 kg bin capacity	NA	658
Top mounted bottled water cooler	NA	114 to 350
Cash register	25	9
Touch screen computer, 380 mm standard LCD and 2.2 GHz processor	NA	58
Self-checkout machine	NA	15

Source: Bach and Sarfraz (2017)
[a]For some equipment, nameplate power consumption is not available, where NA = not available.
[b]For equipment peak heat gain value, highest 15-min interval of recorded data is listed in tables.

Table 11.30 Recommended Load Factors for Various Types of Offices
[2017F, Ch 18, Tbl 11]

Type of Use	Load Factor*, W/m^2	Description
100% laptop, docking station		
light	3.67	15.5 m^2/workstation, all laptop docking station use, 1 printer per 10
medium	4.91	11.6 m^2/workstation, all laptop docking station use, 1 printer per 10
50% laptop, docking station		
light	4.75	15.5 m^2/workstation, 50% laptop docking station/50% desktop, 1 printer per 10
medium	6.35	11.6 m^2/workstation, 50% laptop docking station/50% desktop, 1 printer per 10
100% desktop		
light	5.83	15.5 m^2/workstation, all desktop use, 1 printer per 10
medium	7.79	11.6 m^2/workstation, all desktop use, 1 printer per 10
100% laptop, docking station		
2 screens	7.44	11.6 m^2/workstation, all laptop docking station use, 2 screens, 1 printer per 10
100% desktop		
2 screens	9.06	11.6 m^2/workstation, all laptop use, 2 screens, 1 printer per 10
3 screens	10.33	11.6 m^2/workstation, all desktop use, 3 screens, 1 printer per 10
100% desktop		
heavy, 2 screens	11.00	7.9 m^2/workstation, all desktop use, 2 screens, 1 printer per 8
heavy, 3 screens	12.49	7.9 m^2/workstation, all desktop use, 3 screens, 1 printer per 8
100% laptop, docking station		
full on, 2 screens	12.23	7.9 m^2/workstation, all laptop docking use, 2 screens, 1 printer per 8, no diversity
100% desktop		
full on, 2 screens	14.35	7.9 m^2/workstation, all desktop use, 2 screens, 1 printer per 8, no diversity
full on, 3 screens	16.48	7.9 m^2/workstation, all desktop use, 3 screens, 1 printer per 8, no diversity

Source: Bach and Sarfraz (2017)

*Medium office type monochrome printer is used for load factor calculator with 15- min peak power consumption of 142 W.

Table 11.31 Diversity Factor for Different Equipment [2017F, Ch 18, Tbl 12]

Equipment	Diversity Factor, %	Diversity Factor,[a] %
Desktop PC	75	75
Laptop docking station	70	NA
Notebook computer	75[b]	75
Screen	70	60
Printer	45	NA

Source: Bach and Sarfraz (2017)
[a]2013 *ASHRAE Handbook—Fundamentals*
[b]Insufficient data from RP-1742; values based on previous data from 2013 *ASHRAE Handbook—Fundamentals* and judgment of Bach and Sarfraz (2017).

Table 11.32 Refrigerating Effect Produced by Open Refrigerated Display Fixtures

Type of Display Fixture	W/m of Fixture*		
	Latent Heat	Sensible Heat	Total Refrigerating Effect
Low temperature			
Frozen Food			
Single Deck	36	199	236
Single Deck, Double Island	67	384	452
2 Deck	138	554	692
3 Deck	310	1238	1540
4 or 5 Deck	384	1538	1923
Ice Cream			
Single Deck	62	352	413
Single Deck, Double Island	67	384	452
Standard Temperature			
Meats			
Single Deck	50	286	336
Multideck	211	842	1053
Dairy			
Multideck	188	754	942
Produce			
Single Deck	35	196	231
Multideck	184	738	923

*These figures are general magnitudes for fixtures adjusted for average desired product temperatures and apply to store ambients in front of the display cases of 22°C to 23°C with 50% to 55% rh. Raising the dry bulb only 2°C to 3°C and the humidity 5% to 10% can increase heat removal 25% or more. Equally lower temperatures and humidities as in winter, have an equally marked effect on lowering heat removal from the space.

12. VENTILATION

ASHRAE Standard 62.2-2016, *Ventilation and Acceptable Indoor Air Quality in Residential Buildings*

(*See complete standard for detailed guidance.*)

Residential Ventilation for Single and Multiple Family Structures, Including Manufactured and Modular Houses

Whole-house mechanical ventilation systems are required for each dwelling unit:

$$L/s = 0.15\ (m^2\ \text{floor area}) + 3.5\ (\text{number of bedrooms} + 1) \tag{12.1}$$

Exceptions: (a) building has no mechanical cooling and is in zone 1 or 2 of the climate zone map (see Figure 13.1), or (b) building is thermally conditioned for human occupancy for less than 876 h per year **and** if the authority having jurisdiction determines that window ventilation is sufficient.

Alternate means may be used to provide the required ventilation rate when approved by a licensed design professional. In hot, humid climates, whole-house net mechanical exhaust shall not exceed 35 L/s per 100 m^2. In severe cold climates, net supply systems shall not exceed 35 L/s per 100 m^2. (Climates are defined in Figure 13.1.)

Local mechanical exhaust rates are shown in Tables 12.2 and 12.3.

Ventilation openings: not less than 4% of floor nor less than 0.5 m^2 for habitable rooms; and not less than 4% of floor space nor less than 0.15 m^2 for toilets and utility rooms.

Supply ductwork for thermal conditioners except evaporative coolers, shall have a MERV 6 filter or better in accordance with ASHRAE Standard 52.2.

Airflows all refer to delivered airflow as tested, or the fans' rating at 62.5 Pa with duct sizing meet the prescriptive sizing of Table 12.4.

Table 12.1 Ventilation Air Requirements, cfm [Std 62.2-2016, Tbl 4.1a]

Floor Area, m^2	Bedrooms				
	1	2	3	4	5
<47	14	18	21	25	28
47–93	21	24	28	31	35
94–139	28	31	35	38	42
140–186	35	38	42	45	49
187–232	42	45	49	52	56
233–279	49	52	56	59	63
280–325	56	59	63	66	70
326–372	63	66	70	73	77
373–418	70	73	77	80	84
419–465	77	80	84	87	91

Table 12.2 Demand-Controlled Local Ventilation Exhaust Airflow Rates
[Std 62.2-2016, Tbl 5.1]

Application	Airflow
Enclosed Kitchen	• Vented range hood (including appliance-range hood combinations): 50 L/s • Other kitchen exhaust fans, including downdraft: 150 L/s or a capacity of 5 ach
Nonenclosed Kitchen	• Vented range hood (including appliance-range hood combinations): 50 L/s • Other kitchen exhaust fans, including downdraft: 150 L/s
Bathroom	25 L/s

Table 12.3 Continuous Local Ventilation Exhaust Airflow Rates
[Std 62.2-2016, Tbl 5.2]

Application	Airflow
Enclosed Kitchen	5 ach, based on kitchen volume
Bathroom	10 L/s

Table 12.4 Prescriptive Duct Sizing [Std 62.2-2016, Tbl 5.3]

Duct Type	**Flex Duct**								**Smooth Duct**							
Fan Airflow Rating, L/s @ 62.5 Pa	25	40	50	65	75	100	125	150	25	40	50	65	75	100	125	150
Diameter[a], mm	**Maximum Length[b,c,d], m**															
75	×	×	×	×	×	×	×	×	2	×	×	×	×	×	×	×
100	17	1	×	×	×	×	×	×	35	9	3	×	×	×	×	×
125	NL	25	9	5	0.6	×	×	×	NL	46	28	16	9	1	×	×
150	NL	NL	48	28	17	5	0.3	×	NL	NL	NL	51	34	16	8	3
175	NL	NL	NL	NL	49	724	12	6	NL	NL	NL	NL	NL	45	27	16
200 and above	NL	NL	NL	NL	NL	58	34	21	NL	NL	NL	NL	NL	NL	60	41

a. For noncircular ducts, calculate the diameter as four times the cross-sectional area divided by the perimeter.
b. This table assumes no elbows. Deduct 5 m of allowable duct length for each elbow.
c. NL = no limit on duct length of this size.
d. × = not allowed; any length of duct of this size with assumed turns and fitting will exceed the rated pressure drop.

ASHRAE Standard 62.1-2016, *Ventilation for Acceptable Indoor Air Quality*

(*See complete standard for detailed guidance.*)

General

Use of natural ventilation systems is permitted in lieu of or in conjunction with mechanical ventilation. Naturally ventilated spaces shall be permanently open to operable wall or roof openings to the outdoors; free openable area at least 4% of net occupiable floor area. If interior spaces are ventilated through adjoining rooms, free area between rooms shall be permanently unobstructed and at least 8% of the area of the interior room, nor less than 2.3 m^2. Occupants must have ready access to the openings.

All airstream surfaces shall be designed to resist mold growth and resist erosion. Ductwork construction shall meet SMACNA standards. In accordance with manufacturer instructions, fuel-burning appliances shall have sufficient air for combustion and adequate removal of combustion products, which shall be vented directly outdoors. Filters or air cleaners with minimum MERV 8 by ASHRAE Standard 52.2 shall be provided upstream of all cooling coils or other devices with wetted surfaces through which air is supplied to occupiable space. Relative humidity should be 65% or less when system performance is analyzed with outdoor at the design dew point and mean coincident dry bulb, sensible and latent space interior loads at cooling design values, and space solar loads at zero. Drain pans slope minimum 10 mm per metre to outlet at lowest point, and drain line shall have P-trap or other seal when drain pan is at negative static pressure relative to the outlet. Drain pan shall extend from leading edge of the coil to a distance of half the vertical dimension of the coil.

Discharge from noncombustion equipment that captures contaminants generated by the equipment shall be discharged directly outdoors.

Investigate outdoor air quality. Survey and document local and regional outdoor air quality, with description of noticeable air problems and conditions regarding its acceptability. If unacceptable, treat it. Cleaning for ozone is required only if in a high-ozone area (see Informative Appendix F of the standard) and if the minimum design outdoor airflow is 1.5 air changes or more.

Outdoor air intakes shall be located so the shortest distance from intake to any specific contaminant source shall equal or exceed values in Table 12.5 or that result from the calculation method in Normative Appendix B of ASHRAE Standard 62.1.

Design intakes to manage rain and snow entrainment and include bird screens.

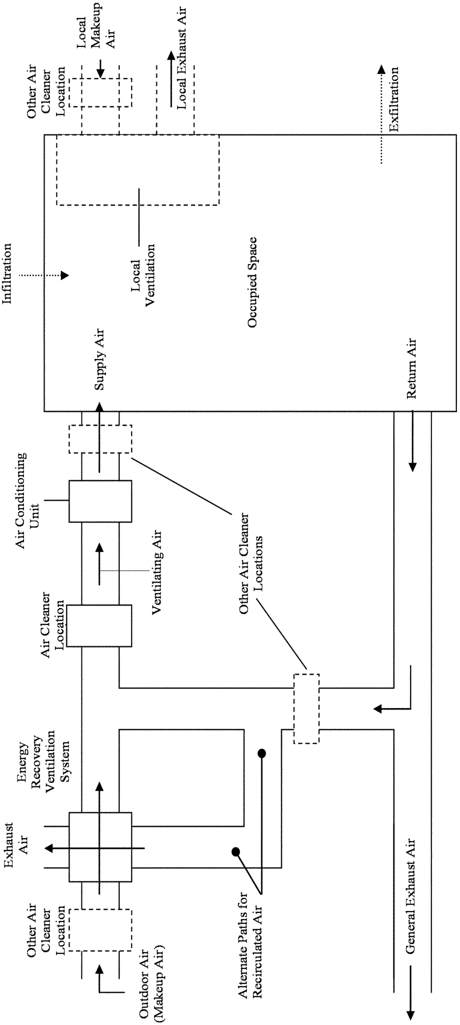


Figure 12.1 Ventilation System [Std 62.1-2016, Fig 3.1]

Table 12.5 Air Intake Minimum Separation Distance [Std 62.1-2016, Tbl 5.5.1]

Object	Minimum Distance, m
Class 2 air exhaust/relief outlet[a]	3
Class 3 air exhaust/relief outlet[a]	5
Class 4 air exhaust/relief outlet[b]	10
Plumbing vents terminating less than 1 m above the level of the outdoor air intake	3
Plumbing vents terminating at least 1 m above the level of the outdoor air intake	1
Vents, chimneys, and flues from combustion appliances and equipment[c]	5
Garage entry, automobile loading area, or drive-in queue[d]	5
Truck loading area or dock, bus parking/idling area[d]	7.5
Driveway, street, or parking place[d]	1.5
Thoroughfare with high traffic volume	7.5
Roof, landscaped grade, or other surface directly below intake[e,f]	0.30
Garbage storage/pick-up area, dumpsters	5
Cooling tower intake or basin	5
Cooling tower exhaust	7.5

a. This requirement applies to the distance from the outdoor air intakes for one ventilation system to the exhaust outlets and relief outlets for any other ventilation system.

b. Minimum distance listed does not apply to laboratory fume hood exhaust air outlets. Separation criteria for fume hood exhaust shall be in compliance with ANSI/AIHA Z9.5. Informative Appendix J contains sources of additional information on separation criteria. These include the *ACGIH Industrial Ventilation Manual*, *ASHRAE Handbook—HVAC Applications*, *ASHRAE Laboratory Design Guide*, and NSF/ANSI 49.

c. The minimum distances relative to fuel-fired appliances shall be as required by ANSI Z223.1/NFPA 54 for fuel gas burning appliances and equipment, NFPA 31 for oil burning appliances and equipment, and NFPA 211 for other combustion appliances and equipment.

d. Distance measured to closest place that vehicle exhaust is likely to be located.

e. The minimum separation distance shall not apply where outdoor surfaces below the air intake are sloped more than 45 degrees from horizontal or where such surfaces are less than 30 mm in width.

f. Where snow accumulation is expected, the surface of the snow at the expected average snow depth shall be considered to be a surface directly below an intake.

Air classifications:

- Class 1: Air with low contaminant concentration, low sensory-irritation intensity, and inoffensive odor.
- Class 2: Air with moderate contaminant concentration, mild sensory-irritation intensity, or mildly offensive odors. (Class 2 air also includes air that is not necessarily harmful or objectionable but that is inappropriate for transfer or recirculation to spaces used for different purposes.)
- Class 3: Air with significant contaminant concentration, significant sensory-irritation intensity, or offensive odor.
- Class 4: Air with highly objectionable fumes or gases or with potentially dangerous particles, bioaerosols, or gases, at concentrations high enough to be considered harmful.

The Ventilation Rate Procedure, the Natural Ventilation Procedure, or the Indoor Air Quality (IAQ) Procedure, or a combination thereof, shall be used to design ventilation systems. The IAQ procedure is based on analysis of contaminant sources, concentrations, and targets, and perceived acceptability targets.

Table 12.6 Airstreams or Sources [Std 62.1-2016, Tbl 5.16.1]

Description	Air Class
Diazo printing equipment discharge	4
Commercial kitchen grease hoods	4
Commercial kitchen hoods other than grease	3
Laboratory hoods	4*
Residential kitchen hoods	3
Hydraulic elevator machine room	2

*Air Class 4 unless determined otherwise by the Environmental Health and Safety professional responsible to the owner or to the owner's designee

Procedures from ASHRAE Standard 62.1-2016

6.1 General. The Ventilation Rate Procedure, the IAQ Procedure, the Natural Ventilation Procedure, or a combination thereof shall be used to meet the requirements of this section. In addition, the requirements for exhaust ventilation in Section 6.5 shall be met regardless of the method used to determine minimum outdoor airflow rates.

Informative Note: Although the intake airflow determined using each of these approaches may differ significantly because of assumptions about the design, any of these approaches is a valid basis for design.

6.1.1 Ventilation Rate Procedure. The prescriptive design procedure presented in Section 6.2, in which outdoor air intake rates are determined based on space type/application, occupancy level, and floor area, shall be permitted to be used for any zone or system.

Informative Note: The Ventilation Rate Procedure minimum rates are based on contaminant sources and source strengths that are typical for the listed occupancy categories.

6.1.2 IAQ Procedure. This performance-based design procedure presented in Section 6.3, in which the building outdoor air intake rates and other system design parameters are based on an analysis of contaminant sources, contaminant concentration limits, and level of perceived indoor air acceptability, shall be permitted to be used for any zone or system.

6.1.3 Natural Ventilation Procedure. The prescriptive design procedure presented in Section 6.4, in which outdoor air is provided through openings to the outdoors, shall be permitted to be used for any zone or portion of a zone in conjunction with mechanical ventilation systems in accordance with Section 6.4.

6.2 Ventilation Rate Procedure. The outdoor air intake flow (V_{ot}) for a ventilation system shall be determined in accordance with Sections 6.2.1 through 6.2.7.

Informative Note: Additional explanation of terms used below is contained in Normative Appendix A, along with a ventilation system schematic (Figure 12.2).

6.2.1 Outdoor Air Treatment. Each ventilation system that provides outdoor air through a supply fan shall comply with the following subsections.

Exception: Systems supplying air for enclosed parking garages, warehouses, storage rooms, janitor's closets, trash rooms, recycling areas, shipping/receiving/distribution areas.

Informative Note: Occupied spaces ventilated with outdoor air that is judged to be unacceptable are subject to reduced air quality when outdoor air is not cleaned prior to introduction to the occupied spaces.

6.2.1.1 Particulate Matter Smaller than 10 Micrometers (PM10). In buildings located in an area where the national standard or guideline for PM10 is exceeded, particle filters or air-cleaning devices shall be provided to clean the outdoor air at any location prior to its introduction to occupied spaces. Particulate matter filters or air cleaners shall have an efficiency reporting value (MERV) of not less than 6 where rated in accordance with ASHRAE Standard 52.2.

Informative Note: See Informative Appendix F for resources regarding selected PM10 national standards and guidelines.

6.2.1.2 Particulate Matter Smaller than 2.5 Micrometers (PM2.5). In buildings located in an area where the national standard or guideline for PM2.5 is exceeded, particle filters or air-cleaning devices shall be provided to clean the outdoor air at any location prior to its introduction to occupied spaces. Particulate matter filters or air cleaners shall have an efficiency reporting value (MERV) of not less than 11 where rated in accordance with ASHRAE Standard 52.2.

Informative Note: See Informative Appendix F for resources regarding selected PM2.5 national standards and guidelines.

6.2.1.3 Ozone. Air-cleaning devices for ozone shall be provided when the most recent three-year average annual fourth-highest daily maximum eight-hour average ozone concentration exceeds 209 $\mu g/m^3$.

Such air-cleaning devices shall have a volumetric ozone removal efficiency of not less than 40% where installed, operated, and maintained in accordance with manufacturer recommendations and shall be approved by the authority having jurisdiction. Such devices shall be operated where the outdoor ozone levels are expected to exceed 209 $\mu g/m^3$.

Exceptions: Air cleaning for ozone shall not be required where

1. the system design outdoor air intake flow is 1.5 ach or less,
2. controls are provided that sense outdoor ozone level and reduce intake airflow to 1.5 ach or less while complying with the outdoor airflow requirements of Section 6, or
3. outdoor air is brought into the building and heated by direct-fired makeup air units.

Informative Note: See Informative Appendix F for a map of United States locations exceeding the most recent three-year average annual fourth-highest daily maximum eight-hour average ozone concentration of 209 $\mu g/m^3$.

6.2.1.4 Other Outdoor Contaminants. In buildings located in an area where the national standard for one or more contaminants not addressed in Section 6.2.1 is exceeded, any design assumptions and calculations related to the impact on indoor air quality shall be included in the design documents.

6.2.2 Zone Calculations. Ventilation zone parameters shall be determined in accordance with Sections 6.2.2.1 through 6.2.2.3 for ventilation zones served by the ventilation system.

6.2.2.1 Breathing Zone Outdoor Airflow. The outdoor airflow required in the breathing zone (V_{bz}) of the occupiable space or spaces in a ventilation zone shall be not less than the value determined in accordance with Equation 12.2:

$$V_{bz} = R_p \times P_z + R_a \times A_z \tag{12.2}$$

where

A_z = zone floor area, the net occupiable floor area of the ventilation zone, m^2

P_z = zone population, the number of people in the ventilation zone during use

R_p = outdoor airflow rate required per person as determined from Table 12.7

Informative Note: These values are based on adapted occupants.

R_a = outdoor airflow rate required per unit area as determined from Table 12.7

Informative Note: Equation 12.2 accounts for people-related sources and area-related sources independently in the determination of the outdoor air rate required at the breathing zone. The use of Equation 12.2 in the context of this standard does not necessarily imply that simple addition of outdoor airflow rates for different sources can be applied to any other aspect of indoor air quality.

6.2.2.1.1 Design Zone Population. Design zone population (P_z) shall equal the largest (peak) number of people expected to occupy the ventilation zone during typical use.

Exceptions:

1. Where the number of people expected to occupy the ventilation zone fluctuates, zone population equal to the average number of people shall be permitted, provided such average is determined in accordance with Section 6.2.6.2.
2. Where the largest or average number of people expected to occupy the ventilation zone cannot be established for a specific design, an estimated value for

zone population shall be permitted, provided such value is the product of the net occupiable area of the ventilation zone and the default occupant density listed in Table 12.7.

6.2.2.2 Zone Air Distribution Effectiveness. The zone air distribution effectiveness (E_z) shall be not greater than the default value determined using Table 6.2.2.2 of Standard 62.1-2016.

Informative Note: For some configurations, the default value depends upon space and supply air temperature.

6.2.2.3 Zone Outdoor Airflow. The zone outdoor airflow (V_{oz}) provided to the ventilation zone by the supply air distribution system shall be determined in accordance with Equation 12.3:

$$V_{oz} = V_{bz}/E_z \tag{12.3}$$

6.2.3 Single-Zone Systems. For ventilation systems wherein one or more air handlers supply a mixture of outdoor air and recirculated air to only one ventilation zone, the outdoor air intake flow (V_{ot}) shall be determined in accordance with Equation 12.4:

$$V_{ot} = V_{oz} \tag{12.4}$$

6.2.4 100% Outdoor Air Systems. For ventilation systems wherein one or more air handlers supply only outdoor air to one or more ventilation zones, the outdoor air intake flow (V_{ot}) shall be determined in accordance with Equation 12.5:

$$V_{ot} = \Sigma_{all\ zones} V_{oz} \tag{12.5}$$

6.2.5 Multiple-Zone Recirculating Systems. For ventilation systems wherein one or more air handlers supply a mixture of outdoor air and recirculated air to more than one ventilation zone, the outdoor air intake flow (V_{ot}) shall be determined in accordance with Sections 6.2.5.1 through 6.2.5.4.

6.2.5.1 Primary Outdoor Air Fraction. Primary outdoor air fraction (Z_{pz}) shall be determined for ventilation zones in accordance with Equation 12.6:

$$Z_{pz} = V_{oz}/V_{pz} \tag{12.6}$$

where V_{pz} is the zone primary airflow to the ventilation zone, including outdoor air and recirculated air.

a. For VAV-system design purposes, V_{pz} is the lowest zone primary airflow value expected at the design condition analyzed.
b. In some cases, it is permitted to determine these parameters for only selected zones as outlined in Normative Appendix A.

6.2.5.2 System Ventilation Efficiency. The system ventilation efficiency (E_v) shall be determined in accordance with Table 6.2.5.2 or Normative Appendix A of Standard 62.1-2016.

6.2.5.3 Uncorrected Outdoor Air Intake. The uncorrected outdoor air intake (V_{ou}) flow shall be determined in accordance with Equation 12.7:

$$V_{ou} = D\Sigma_{all\ zones}(R_p \times P_z) + \Sigma_{all\ zones}(R_a \times A_z) \tag{12.7}$$

6.2.5.3.1 Occupant Diversity. The occupant diversity ratio (D) shall be determined in accordance with Equation 12.8 to account for variations in population within the ventilation zones served by the system.

$$D = P_s/\Sigma_{all\ zones} P_z \tag{12.8}$$

where the system population (P_s) is the total population in the area served by the system.

Exception: Alternative methods to account for occupant diversity shall be permitted, provided the resulting V_{ou} value is not less than that determined using Equation 12.7.

Informative Note: The uncorrected outdoor air intake (V_{ou}) is adjusted for occupant diversity, but it is not corrected for system ventilation efficiency.

Table 12.7 Minimum Ventilation Rates in Breathing Zone

Std 62.1-2016, Tbl 6.2.2.1]

(Table 12.7 shall be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p L/s·person	Area Outdoor Air Rate R_a L/s·m^2	Notes	Default Values: Occupant Density (see Note 4) #/100 m^2	Default Values: Combined Outdoor Air Rate (see Note 5) L/s·person	Air Class
Correctional Facilities						
Cell	2.5	0.6		25	4.9	2
Dayroom	2.5	0.3		30	3.5	1
Guard stations	2.5	0.3		15	4.5	1
Booking/waiting	3.8	0.3		50	4.4	2
Educational Facilities						
Daycare (through age 4)	5	0.9		25	8.6	2
Daycare sickroom	5	0.9		25	8.6	3
Classrooms (ages 5–8)	5	0.6		25	7.4	1
Classrooms (age 9 plus)	5	0.6		35	6.7	1
Lecture classroom	3.8	0.3	H	65	4.3	1
Lecture hall (fixed seats)	3.8	0.3	H	150	4.0	1
Art classroom	5	0.9		20	9.5	2
Science laboratories	5	0.9		25	8.6	2
University/college laboratories	5	0.9		25	8.6	2
Wood/metal shop	5	0.9		20	9.5	2
Computer lab	5	0.6		25	7.4	1
Media center	5	0.6	A	25	7.4	1
Music/theater/dance	5	0.3	H	35	5.9	1
Multiuse assembly	3.8	0.3	H	100	4.1	1
Food and Beverage Service						
Restaurant dining rooms	3.8	0.9		70	5.1	2
Cafeteria/fast-food dining	3.8	0.9		100	4.7	2
Bars, cocktail lounges	3.8	0.9		100	4.7	2
Kitchen (cooking)	3.8	0.6		20	7.0	2
General						
Break rooms	2.5	0.3	H	25	3.5	1
Coffee stations	2.5	0.3	H	20	4	1
Conference/meeting	2.5	0.3	H	50	3.1	1
Corridors	—	0.3	H	—		1
Occupiable storage rooms for liquids or gels	2.5	0.6	B	2	32.5	2
Hotels, Motels, Resorts, Dormitories						
Bedroom/living room	2.5	0.3	H	10	5.5	1
Barracks sleeping areas	2.5	0.3	H	20	4.0	1
Laundry rooms, central	2.5	0.6		10	8.5	2
Laundry rooms within dwelling units	2.5	0.6		10	8.5	1
Lobbies/prefunction	3.8	0.3	H	30	4.8	1
Multipurpose assembly	2.5	0.3	H	120	2.8	1
Office Buildings						
Breakrooms	2.5	0.6		50	3.5	1
Main entry lobbies	2.5	0.3	H	10	5.5	1
Occupiable storage rooms for dry materials	2.5	0.3		2	17.5	1
Office space	2.5	0.3	H	5	8.5	1
Reception areas	2.5	0.3	H	30	3.5	1
Telephone/data entry	2.5	0.3	H	60	3.0	1

Table 12.7 Minimum Ventilation Rates in Breathing Zone
Std 62.1-2016, Tbl 6.2.2.1] ***(Continued)***
(Table 12.7 shall be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p L/s·person	Area Outdoor Air Rate R_a L/s·m²	Notes	Default Values: Occupant Density (see Note 4) #/100 m²	Default Values: Combined Outdoor Air Rate (see Note 5) L/s·person	Air Class
Miscellaneous Spaces						
Bank vaults/safe deposit	2.5	0.3	H	5	8.5	2
Banks or bank lobbies	3.8	0.3	H	15	6.0	1
Computer (not printing)	2.5	0.3	H	4	10.0	1
Freezer and refrigerated spaces (<50°F)	5	0	E	0	0	2
General manufacturing (excludes heavy industrial and processes using chemicals)	5.0	0.9		7	18	3
Pharmacy (prep. area)	2.5	0.9		10	11.5	2
Photo studios	2.5	0.6		10	8.5	1
Shipping/receiving	5	0.6	B	2	35	2
Sorting, packing, light assembly	3.8	0.6		7	12.5	2
Telephone closets	—	0.0		—		1
Transportation waiting	3.8	0.3	H	100	4.1	1
Warehouses	5	0.3	B	—		2
Public Assembly Spaces						
Auditorium seating area	2.5	0.3	H	150	2.7	1
Places of religious worship	2.5	0.3	H	120	2.8	1
Courtrooms	2.5	0.3	H	70	2.9	1
Legislative chambers	2.5	0.3	H	50	3.1	1
Libraries	2.5	0.6		10	8.5	1
Lobbies	2.5	0.3	H	150	2.7	1
Museums (children's)	3.8	0.6		40	5.3	1
Museums/galleries	3.8	0.3	H	40	4.6	1
Residential						
Dwelling unit	2.5	0.3	F,G, H	F		1
Common corridors	—	0.3	H			1
Retail						
Sales (except as below)	3.8	0.6		15	7.8	2
Mall common areas	3.8	0.3	H	40	4.6	1
Barbershop	3.8	0.3	H	25	5.0	2
Beauty and nail salons	10	0.6		25	12.4	2
Pet shops (animal areas)	3.8	0.9		10	12.8	2
Supermarket	3.8	0.3	H	8	7.6	1
Coin-operated laundries	3.8	0.6		20	7.0	2
Sports and Entertainment						
Gym, sports arena (play area)	10	0.9	E	7	23	2
Spectator areas	3.8	0.3	H	150	4.0	1
Swimming (pool & deck)	—	2.4	C	—		2
Disco/dance floors	10	0.3	H	100	10.3	2
Health club/aerobics room	10	0.3		40	10.8	2
Health club/weight rooms	10	0.3		10	13.0	2
Bowling alley (seating)	5	0.6		40	6.5	1
Gambling casinos	3.8	0.9		120	4.6	1
Game arcades	3.8	0.9		20	8.3	1
Stages, studios	5	0.3	D, H	70	5.4	1

GENERAL NOTES FOR TABLE 12.7

1 Related requirements: The rates in this table are based on all other applicable requirements of this standard being met.

2 Environmental Tobacco Smoke: This table applies to ETS-free areas. Refer to Section 5.17 for requirements for buildings containing ETS areas and ETS-free areas.

3 Air density: Volumetric airflow rates are based on dry air density of 1.2 kg_{da}/m^3 at a barometric pressure of 101.3 kPa and an air temperature of 21°C. Rates shall be permitted to be adjusted for actual density.

4 Default occupant density: The default occupant density shall be used where the actual occupant density is not known.

5 Default combined outdoor air rate (per person): Rate is based on the default occupant density.

6 Unlisted occupancies: Where the occupancy category for a proposed space or zone is not listed, the requirements for the listed occupancy category that is most similar in terms of occupant density, activities, and building construction shall be used.

ITEM-SPECIFIC NOTES FOR TABLE 12.7

A For high-school and college libraries, the values shown for "Public Assembly Spaces—Libraries" shall be used.

B Rate may not be sufficient where stored materials include those having potentially harmful emissions.

C Rate does not allow for humidity control. "Deck area" refers to the area surrounding the pool that is capable of being wetted during pool use or when the pool is occupied. Deck area that is not expected to be wetted shall be designated as an occupancy category.

D Rate does not include special exhaust for stage effects such as dry ice vapors and smoke.

E Where combustion equipment is intended to be used on the playing surface or in the space, additional dilution ventilation, source control, or both shall be provided.

F Default occupancy for dwelling units shall be two persons for studio and one-bedroom units, with one additional person for each additional bedroom.

G Air from one residential dwelling shall not be recirculated or transferred to any other space outside of that dwelling.

H Ventilation air for this occupancy category shall be permitted to be reduced to zero when the space is in occupied-standby mode.

6.2.5.3.2 Design System Population. Design system population (P_s) shall equal the largest (peak) number of people expected to occupy all ventilation zones served by the ventilation system during use.

Informative Note: Design system population is always equal to or less than the sum of design zone population for all zones in the area served by the system because all zones may not be simultaneously occupied at design population.

6.2.5.4 Outdoor Air Intake. The design outdoor air intake flow (V_{ot}) shall be determined in accordance with Equation 12.9:

$$V_{ot} = V_{ou}/E_v \tag{12.9}$$

6.2.6 Design for Varying Operating Conditions

6.2.6.1 Variable Load Conditions. Ventilation systems shall be designed to be capable of providing not less than the minimum ventilation rates required in the breathing zone where the zones served by the system are occupied, including all full- and part-load conditions.

Informative Note: The minimum outdoor air intake flow may be less than the design value at part-load conditions.

6.2.6.2 Short-Term Conditions. Where it is known that peak occupancy will be of short duration, ventilation will be varied or interrupted for a short period of time, or both, the design shall be permitted to be based on the average conditions over a time period (T) determined by Equation 12.10:

$$T = 50v/V_{bz} \tag{12.10}$$

where

T = averaging time period, min

v = the volume of the ventilation zone where averaging is being applied, m^3

V_{bz} = the breathing zone outdoor airflow calculated using Equation 12.2 and the design value of the zone population (P_z), L/s

Acceptable design adjustments based on this optional provision include the following:

a. Zones with fluctuating occupancy: The zone population (P_z) shall be permitted to be averaged over time (T).

Table 12.8 System Ventilation Efficiency [Std 62.1-2016, Tbl 6.2.5.1]

Max (Z_{pz})	E_v
≤0.15	1.0
≤0.25	0.9
≤0.35	0.8
≤0.45	0.7
≤0.55	0.6
>0.55	Use Normative Appendix A of Standard 62.1-2016

NOTES:
1. "Max (Z_{pz})" refers to the largest value of Z_{pz}, calculated using Equation 12.6, among all the ventilation zones served by the system.
2. For values of Max (Z_{pz}) between 0.15 and 0.55, the corresponding value of E_v may be determined by interpolating the values in the table.
3. The values of E_v in this table are based on a 0.15 average outdoor air fraction for the system. For systems with higher values of the average outdoor air fraction, this table may result in unrealistically low values of E_v and the use of Normative Appendix A may yield more practical results.

b. Zones with intermittent interruption of supply air: The average outdoor airflow supplied to the breathing zone over time (T) shall be not less than the breathing zone outdoor airflow (V_{bz}) calculated using Equation 12.2.
c. Systems with intermittent closure of the outdoor air intake: The average outdoor air intake over time (T) shall be not less than the minimum outdoor air intake (V_{ot}) calculated using Equation 12.4, 12.5, or 12.9 as appropriate.

6.2.7 Dynamic Reset. The system shall be permitted to be designed to reset the outdoor air intake flow (V_{ot}), the space or ventilation zone airflow (V_{oz}) as operating conditions change, or both.

6.2.7.1 Demand Control Ventilation (DCV). DCV shall be permitted as an optional means of dynamic reset.

Exception: CO_2-based DCV shall not be applied in zones with indoor sources of CO_2 other than occupants or with CO_2 removal mechanisms, such as gaseous air cleaners.

6.2.7.1.1 For DCV zones in the occupied mode, breathing zone outdoor airflow (V_{bz}) shall be reset in response to current population.

6.2.7.1.2 For DCV zones in the occupied mode, breathing zone outdoor airflow (V_{bz}) shall be not less than the building component ($R_a \times A_z$) for the zone.

Exception: Breathing zone outdoor airflow shall be permitted to be reduced to zero for zones in occupied standby mode for the occupancy categories indicated in Table 12.7, provided that airflow is restored to V_{bz} whenever occupancy is detected.

6.2.7.1.3 Documentation. A written description of the equipment, methods, control sequences, setpoints, and the intended operational functions shall be provided. A table shall be provided that shows the minimum and maximum outdoor intake airflow for each system.

6.2.7.2 Ventilation Efficiency. Variations in the efficiency with which outdoor air is distributed to the occupants under different ventilation system airflows and temperatures shall be permitted as an optional basis of dynamic reset.

6.2.7.3 Outdoor Air Fraction. A higher fraction of outdoor air in the air supply due to intake of additional outdoor air for free cooling or exhaust air makeup shall be permitted as an optional basis of dynamic reset.

6.3 Indoor Air Quality (IAQ) Procedure. Breathing zone outdoor airflow (V_{bz}) shall be determined in accordance with Sections 6.3.1 through 6.3.5.

6.3.1 Contaminant Sources. Each contaminant of concern, for purposes of the design, shall be identified. For each contaminant of concern, indoor sources and outdoor sources shall be identified, and the emission rate for each contaminant of concern from each source shall be determined. Where two or more contaminants of concern target the same organ system, these contaminants shall be considered to be a contaminant mixture.

Informative Note: Informative Appendix C provides information for some potential contaminants of concern, including the organs they affect.

6.3.2 Contaminant Concentration. For each contaminant of concern, a concentration limit and its corresponding exposure period and an appropriate reference to a cognizant authority shall be specified. For each contaminant mixture of concern, the ratio of the concentration of each contaminant to its concentration limit shall be determined, and the sum of these ratios shall be not greater than one.

Exception: Consideration of odors in determining concentration limits shall not be required.

Informative Note:

1. Odors are addressed in Section 6.3.4.2.
2. Informative Appendix C includes concentration guidelines for some potential contaminants of concern.

6.3.3 Perceived Indoor Air Quality. The design level of indoor air acceptability shall be specified in terms of the percentage of building occupants, visitors, or both expressing satisfaction with perceived IAQ.

6.3.4 Design Approach. Zone and system outdoor airflow rates shall be the larger of those determined in accordance with Section 6.3.4.1 and either Section 6.3.4.2 or 6.3.4.3, based on emission rates, concentration limits, and other relevant design parameters.

6.3.4.1 Mass Balance Analysis. Using a steady-state or dynamic mass-balance analysis, the minimum outdoor airflow rates required to achieve the concentration limits specified in Section 6.3.2 shall be determined for each contaminant or contaminant mixture of concern within each zone served by the system.

Informative Note:

1. Informative Appendix E includes steady-state mass-balance equations that describe the impact of air cleaning on outdoor air and recirculation rates for ventilation systems serving a single zone.
2. In the completed building, measurement of the concentration of contaminants or contaminant mixtures of concern may be useful as a means of checking the accuracy of the design mass-balance analysis, but such measurement is not required for compliance.

6.3.4.2 Subjective Evaluation. Using a subjective occupant evaluation conducted in the completed building, the minimum outdoor airflow rates required to achieve the level of acceptability specified in Section 6.3.3 shall be determined within each zone served by the system.

Informative Note:

1. Informative Appendix C presents one approach to subjective occupant evaluation.
2. Level of acceptability often increases in response to increased outdoor airflow rates, increased level of indoor or outdoor air cleaning, or decreased indoor or outdoor contaminant emission rate.

6.3.4.3 Similar Zone. The minimum outdoor airflow rates shall be not less than those found in accordance with Section 6.3.4.2 for a substantially similar zone.

6.3.5 Combined IAQ Procedure and Ventilation Rate Procedure. The IAQ Procedure in conjunction with the Ventilation Rate Procedure shall be permitted to be applied to a zone or system. In this case, the Ventilation Rate Procedure shall be used to determine the required zone minimum outdoor airflow, and the IAQ Procedure shall be used to determine the additional outdoor air or air cleaning necessary to achieve the concentration limits of the contaminants and contaminant mixtures of concern.

Informative Note: The improvement of indoor air quality through the use of air cleaning or provision of additional outdoor air in conjunction with minimum ventilation rates may be quantified using the IAQ Procedure.

6.3.6 Documentation. Where the IAQ Procedure is used, the following information shall be included in the design documentation: the contaminants and contaminant mixtures of concern considered in the design process, the sources and emission rates of the contaminants of concern, the concentration limits and exposure periods and the references for these limits, and the analytical approach used to determine ventilation rates and air-cleaning requirements. The contaminant monitoring and occupant or visitor evaluation plans shall also be included in the documentation.

6.4 Natural Ventilation Procedure. Natural ventilation systems shall be designed in accordance with this section and shall include mechanical ventilation systems designed in accordance with Section 6.2, Section 6.3, or both.

Exceptions:

1. An engineered natural ventilation system, where approved by the authority having jurisdiction, need not meet the requirements of Section 6.4.
2. The mechanical ventilation systems shall not be required where
   a. natural ventilation openings that comply with the requirements of Section 6.4 are permanently open or have controls that prevent the openings from being closed during periods of expected occupancy or
   b. the zone is not served by heating or cooling equipment.

6.4.1 Floor Area to Be Ventilated. Spaces, or portions of spaces, to be naturally ventilated shall be located within a distance based on the ceiling height, as determined by Sections 6.4.1.1, 6.4.1.2, or 6.4.1.3, from operable wall openings that meet the requirements of Section 6.4.2. For spaces with ceilings that are not parallel to the floor, the ceiling height shall be determined in accordance with Section 6.4.1.4.

6.4.1.1 Single Side Opening. For spaces with operable openings on one side of the space, the maximum distance from the operable openings shall be not more than $2H$, where H is the ceiling height.

6.4.1.2 Double Side Opening. For spaces with operable openings on two opposite sides of the space, the maximum distance from the operable openings shall be not more than $5H$, where H is the ceiling height.

6.4.1.3 Corner Openings. For spaces with operable openings on two adjacent sides of a space, the maximum distance from the operable openings shall be not more than $5H$ along a line drawn between the two openings that are farthest apart. Floor area outside that line shall comply with Section 6.4.1.1.

6.4.1.4 Ceiling Height. The ceiling height (H) to be used in Sections 6.4.1.1 through 6.4.1.3 shall be the minimum ceiling height in the space.

Exception: For ceilings that are increasing in height as distance from the openings is increased, the ceiling height shall be determined as the average height of the ceiling within (20 ft) from the operable openings.

6.4.2 Location and Size of Openings. Spaces or portions of spaces to be naturally ventilated shall be permanently open to operable wall openings directly to the outdoors. The openable area shall be not less than 4% of the net occupiable floor area. Where openings are covered with louvers or otherwise obstructed, openable area shall be based on the net free unobstructed area through the opening. Where interior rooms, or portions of rooms, without direct openings to the outdoors are ventilated through adjoining rooms, the opening between rooms shall be permanently unobstructed and have a free area of not less than 8% of the area of the interior room or less than (2.3 m^2).

6.4.3 Control and Accessibility. The means to open required operable openings shall be readily accessible to building occupants whenever the space is occupied. Controls shall be designed to coordinate operation of the natural and mechanical ventilation systems.

6.5 Exhaust Ventilation. The Prescriptive Compliance Path or the Performance Compliance Path shall be used to meet the requirements of this section. Exhaust makeup air shall be permitted to be any combination of outdoor air, recirculated air, or transfer air.

6.5.1 Prescriptive Compliance Path. The design exhaust airflow shall be determined in accordance with the requirements in Table 6.5 of Standard 62.1-2016.

6.5.2 Performance Compliance Path. The exhaust airflow shall be determined in accordance with the following subsections.

6.5.2.1 Contaminant Sources. Contaminants or mixtures of concern for purposes of the design shall be identified. For each contaminant or mixture of concern, indoor sources (occupants, materials, activities, and processes) and outdoor sources shall be identified, and the emission rate for each contaminant of concern from each source shall be determined.

Informative Note: Informative Appendix C provides information for some potential contaminants of concern.

6.5.2.2 Contaminant Concentration. For each contaminant of concern, a concentration limit and its corresponding exposure period and an appropriate reference to a cognizant authority shall be specified.

Informative Note: Informative Appendix C includes concentration guidelines for some potential contaminants of concern.

6.5.2.3 Monitoring and control systems shall be provided to automatically detect contaminant levels of concern and modulate exhaust airflow such that contaminant levels are maintained at not greater than the specified contaminant concentration limits.

6.6 Design Documentation Procedures. Design criteria and assumptions shall be documented and made available for operation of the system after installation. See Sections 4.3, 5.1.3, 5.16.4, 6.2.7.1.4, and 6.3.6 regarding assumptions to be detailed in the documentation.

NORMATIVE APPENDIX A
MULTIPLE-ZONE SYSTEMS

This appendix presents an alternative procedure for calculating the system ventilation efficiency (E_v) that must be used when Standard 62.1-2016 Table 6.2.5.2 values are not used. In this alternative procedure, E_v is equal to the lowest calculated value of the zone ventilation efficiency (E_{vz}) (see Equation 12.12 below).

Informative Note: Figure 12.2 contains a ventilation system schematic depicting most of the quantities used in this appendix.

A1. SYSTEM VENTILATION EFFICIENCY

For any multiple-zone recirculating system, the system ventilation efficiency (E_v) shall be calculated in accordance with Sections A1.1 through A1.3.

A1.1 Average Outdoor Air Fraction. The average outdoor air fraction (X_s) for the ventilation system shall be determined in accordance with Equation 12.11:

$$X_s = V_{ou}/V_{ps} \tag{12.11}$$

where the uncorrected outdoor air intake (V_{ou}) is found in accordance with Section 6.2.5.3, and the system primary airflow (V_{ps}) is found at the condition analyzed.

Informative Note: For VAV-system design purposes, V_{ps} is the highest expected system primary airflow at the design condition analyzed. System primary airflow at design is usually less than the sum of design zone primary airflow values because primary airflow seldom peaks simultaneously in all VAV zones.

A1.2 Zone Ventilation Efficiency. The zone ventilation efficiency (E_{vz}) shall be determined in accordance with Section A1.2.1 or A1.2.2.

A1.2.1 Single Supply Systems. For single supply systems, wherein all of the air supplied to each ventilation zone is a mixture of outdoor air and system-level recirculated air, zone ventilation efficiency (E_{vz}) shall be determined in accordance with Equation 12.12. Examples of single supply systems include constant-volume reheat, single-duct VAV, single-fan dual-duct, and multizone systems.

$$E_{vz} = 1 + X_s - Z_{pz} \tag{12.12}$$

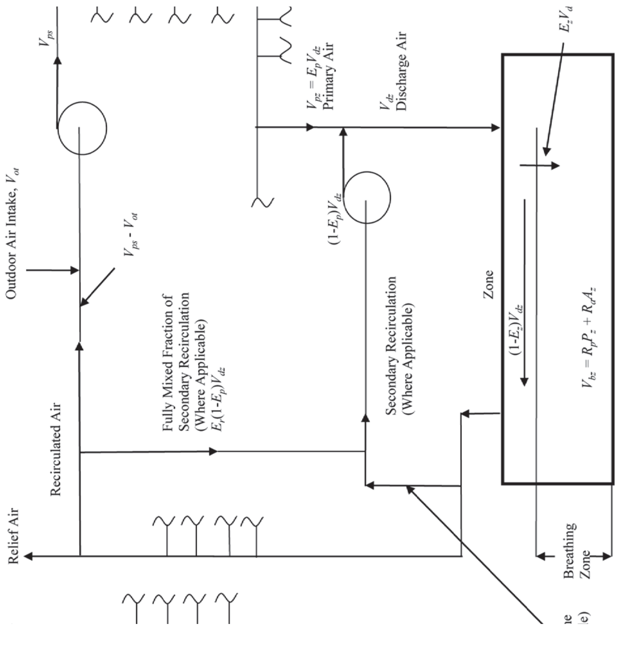


Figure 12.2 Ventilation System Schematic [Std 62.1-2016, Fig A.1]

where the average outdoor air fraction for the system (X_s) is determined in accordance with Equation 12.11, and the primary outdoor air fraction for the zone (Z_{pz}) is determined in accordance with Section 6.2.5.1.

A1.2.2 Secondary Recirculation Systems. For secondary recirculation systems wherein all or part of the supply air to each ventilation zone is recirculated air (air that has not been directly mixed with outdoor air) from other zones, zone ventilation efficiency (E_{vz}) shall be determined in accordance with Equation 12.13. Examples of secondary recirculation systems include dual-fan dual-duct and fan-powered mixing-box systems, and systems that include transfer fans for conference rooms.

$$E_{vz} = (F_a + X_s \times F_b - Z_{pz} \times E_p \times F_c)/F_a \tag{12.13}$$

where system air fractions F_a, F_b, and F_c are determined in accordance with Equations 12.14, 12.15, and 12.16, respectively.

$$F_a = E_p + (1 - E_p) \times E_r \tag{12.14}$$

$$F_b = E_p \tag{12.15}$$

$$F_c = 1 - (1 - E_z) \times (1 - E_r) \times (1 - E_p) \tag{12.16}$$

Where the zone primary air fraction (E_p) is determined in accordance with Equation 12.17, zone secondary recirculation fraction (E_r) is determined by the designer based on system configuration, and zone air distribution effectiveness (E_z) is determined in accordance with Section 6.2.2.2.

$$E_p = V_{pz}/V_{dz} \tag{12.17}$$

where V_{dz} is zone discharge airflow.

Informative Notes:

1. For plenum return systems with secondary recirculation (e.g., fan-powered VAV with plenum return), E_r is usually less than 1.0, although values may range from 0.1 to 1.2, depending upon the location of the ventilation zone relative to other zones and the air handler. For ducted return systems with secondary recirculation (e.g., fan-powered VAV with ducted return), E_r is typically 0.0, while for those with system-level recirculation (e.g, dual-fan dual-duct systems with ducted return), E_r is typically 1.0. For other system types, E_r is typically 0.75.
2. For single-zone and single-supply systems, E_p *is* 1.0.

A1.3 System Ventilation Efficiency. The system ventilation efficiency shall equal the lowest zone ventilation efficiency among all ventilation zones served by the air handler in accordance with Equation 12.18:

$$E_v = \text{minimum } (E_{vz}) \tag{12.18}$$

A2. DESIGN PROCESS

The system ventilation efficiency and, therefore, the outdoor air intake flow for the system (V_{ot}) determined as part of the design process are based on the design and minimum expected supply airflows to individual ventilation zones as well as the design outdoor air requirements to the zones. For VAV system design purposes, zone ventilation efficiency (E_{vz}) for each ventilation zone shall be found using the minimum expected zone primary airflow (V_{pz}) and using the highest expected system primary airflow (V_{ps}) at the design condition analyzed.

Informative Note: Increasing the zone supply airflow values during the design process, particularly to the critical zones requiring the highest fraction of outdoor air, reduces the system outdoor air intake flow requirement determined in the calculation.

A2.1 Selecting Zones for Calculation. Zone ventilation efficiency (E_{vz}) shall be calculated for all ventilation zones.

Exception: Because system ventilation efficiency (E_v) is determined by the minimum value of the zone ventilation efficiency (E_{vz}) in accordance with Equation 12.18, calculation of is not required for any ventilation zone that has an E_{vz} value that is equal to or larger than that of the ventilation zone for which a calculation has been made.

Informative Note: The value of E_{vz} for a ventilation zone will be equal to or larger than that for another ventilation zone if all of the following are true relative to the other ventilation zone:

a. Floor area per occupant (A_z/P_z) is no lower.
b. Minimum zone discharge airflow rate per unit area (V_{dz}/A_z) is no lower.
c. Primary air fraction (E_p) is no lower.
d. Zone air distribution effectiveness (E_z) is no lower.
e. Area outdoor air rate (R_a) is no higher.
f. People outdoor air rate (R_p) is no higher.

A3. SYMBOLS

A_z ***zone floor area:*** the net occupiable floor area of the ventilation zone, m^2.

D ***occupant diversity:*** the ratio of the system population to the sum of the zone populations.

E_p ***primary air fraction:*** the fraction of primary air in the discharge air to the ventilation zone

E_r ***secondary recirculation fraction:*** in systems with secondary recirculation of return air, the fraction of secondary recirculated air to the zone that is representative of average system return air rather than air directly recirculated from the zone.

E_v ***system ventilation efficiency:*** the efficiency with which the system distributes air from the outdoor air intake to the breathing zone in the ventilation-critical zone, which requires the largest fraction of outdoor air in the primary airstream. E_v shall be determined in accordance with Section 6.2.5.2 or Section A1.

E_{vz} ***zone ventilation efficiency:*** the efficiency with which the system distributes air from the outdoor air intake to the breathing zone in any particular ventilation zone.

E_z ***zone air distribution effectiveness:*** a measure of the effectiveness of supply air distribution to the breathing zone. E_z is determined in accordance with Section 6.2.2.2.

F_a ***supply air fraction:*** the fraction of supply air to the ventilation zone that includes sources of air from outside the zone.

F_b ***mixed-air fraction:*** the fraction of supply air to the ventilation zone from fully mixed primary air.

F_c ***outdoor air fraction:*** the fraction of outdoor air to the ventilation zone that includes sources of air from outside the zone.

P_s ***system population:*** the simultaneous number of occupants in the area served by the ventilation system.

P_z ***zone population:*** see Section 6.2.2.1.

R_a ***area outdoor air rate:*** see Section 6.2.2.1.

R_p ***people outdoor air rate:*** see Section 6.2.2.1.

V_{bz} ***breathing zone outdoor airflow:*** see Section 6.2.2.1.

V_{dz} ***zone discharge airflow:*** the expected discharge (supply) airflow to the zone that includes primary airflow and secondary recirculated airflow, cfm (L/s).

V_{ot} ***outdoor air intake flow:*** see Sections 6.2.3, 6.2.4, and 6.2.5.4.

V_{ou} ***uncorrected outdoor air intake:*** see Section 6.2.5.3.

V_{oz} ***zone outdoor airflow:*** see Section 6.2.2.3.

V_{ps} ***system primary airflow:*** the total primary airflow supplied to all zones served by the system from the air-handling unit at which the outdoor air intake is located.

V_{pz} ***zone primary airflow:*** see Section 6.2.5.1.

X_s ***average outdoor air fraction:*** at the primary air handler, the fraction of outdoor air intake flow in the system primary airflow.

Z_{pz} ***primary outdoor air fraction:*** the outdoor air fraction required in the primary air supplied to the ventilation zone prior to the introduction of any secondary recirculation air.

Table 12.9 Design Parameters [Std 170-2013, Tbl 7.1]

(See complete standard for detailed guidance.)

Function of Space	Pressure Relationship to Adjacent Areas (n)	Minimum Outdoor ach	Minimum Total ach	All Room Air Exhausted Directly to Outdoors (j)	Air Recirculated by Means of Room Units (a)	Design Relative Humidity (k), %	Design Temp. (l), °C
SURGERY AND CRITICAL CARE							
Operating room (Class B and C) (m), (n), (o)	Positive	4	20	NR	No	20–60	20–24
Operating/surgical cystoscopic rooms, (m), (n) (o)	Positive	4	20	NR	No	20–60	20–24
Delivery room (Caesarean) (m), (n), (o)	Positive	4	20	NR	No	20–60	20–24
Substerile service area	NR	2	6	NR	No	NR	NR
Recovery room	NR	2	6	NR	No	20–60	21–24
Critical and intensive care	NR	2	6	NR	No	30–60	21–24
Intermediate care (s)	NR	2	6	NR	NR	max 60	21–24
Wound intensive care (burn unit)	NR	2	6	NR	No	40–60	21–24
Newborn intensive care	Positive	2	6	NR	No	30–60	22–26
Treatment room (p)	NR	2	6	NR	NR	20–60	21–24
Trauma room (crisis or shock) (c)	Positive	3	15	NR	No	20–60	21–24
Medical/anesthesia gas storage (r)	Negative	NR	8	Yes	NR	NR	NR
Laser eye room	Positive	3	15	NR	No	20–60	21–24
ER waiting rooms	Negative	2	12	Yes (q)	NR	max 65	21–24
Triage	Negative	2	12	Yes (q)	NR	max 60	21–24
ER decontamination	Negative	2	12	Yes	No	NR	NR
Radiology waiting rooms	Negative	2	12	Yes (q), (w)	NR	max 60	21–24
Procedure room (Class A surgery) (o), (d)	Positive	3	15	NR	No	20–60	21–24
Emergency department exam/treatment room (p)	NR	2	6	NR	NR	max 60	21–24
INPATIENT NURSING							
Patient room	NR	2	4 (y)	NR	NR	max 60	21–24
Nourishment area or room	NR	NR	2	NR	NR	NR	NR
Toilet room	Negative	NR	10	Yes	No	NR	NR
Newborn nursery suite	NR	2	6	NR	No	30–60	22–26
Protective environment room (t)	Positive	2	12	NR	No	max 60	21–24
AII room (u)	Negative	2	12	Yes	No	max 60	21–24
Combination AII/PE room	Positive	2	12	Yes	No	Max 60	21–24
AII anteroom (u)	(e)	NR	10	Yes	No	NR	NR
PE anteroom (t)	(e)	NR	10	NR	No	NR	NR
Combination AII/PE anteroom	(e)	NR	10	Yes	No	NR	NR
Labor/delivery/recovery/postpartum (LDRP) (s)	NR	2	6	NR	NR	max 60	21–24
Labor/delivery/recovery (LDR) (s)	NR	2	6	NR	NR	max 60	21–24
Patient Corridor	NR	NR	2	NR	NR	NR	NR
NURSING FACILITY							
Resident room	NR	2	2	NR	NR	NR	21–24
Resident gathering/activity/dining	NR	4	4	NR	NR	NR	21–24
Resident unit corridor	NR	NR	4	NR	NR	NR	NR
Physical therapy	Negative	2	6	NR	NR	NR	21–24
Occupational therapy	NR	2	6	NR	NR	NR	21–24
Bathing room	Negative	NR	10	Yes	No	NR	21–24
RADIOLOGY (v)							
X-ray (diagnostic and treatment)	NR	2	6	NR	NR	max 60	22–26
X-ray (surgery/critical care and catheterization)	Positive	3	15	NR	No	max 60	21–24
Darkroom (g)	Negative	2	10	Yes	No	NR	NR

Table 12.9 Design Parameters *(Continued)* [Std 170-2013, Tbl 7.1] *(Continued)*

(See complete standard for detailed guidance.)

Function of Space	Pressure Relationship to Adjacent Areas (n)	Minimum Outdoor ach	Minimum Total ach	All Room Air Exhausted Directly to Outdoors (j)	Air Recirculated by Means of Room Units (a)	Design Relative Humidity (k), %	Design Temp. (l), °C
DIAGNOSTIC AND TREATMENT							
Bronchoscopy, sputum collection, and pentamidine administration (n)	Negative	2	12	Yes	No	NR	20–23
Laboratory, general (v)	Negative	2	6	NR	NR	NR	21–24
Laboratory, bacteriology (v)	Negative	2	6	Yes	NR	NR	21–24
Laboratory, biochemistry (v)	Negative	2	6	Yes	NR	NR	21–24
Laboratory, cytology (v)	Negative	2	6	Yes	NR	NR	21–24
Laboratory, glasswashing	Negative	2	10	Yes	NR	NR	NR
Laboratory, histology (v)	Negative	2	6	Yes	NR	NR	21–24
Laboratory, microbiology (v)	Negative	2	6	Yes	NR	NR	21–24
Laboratory, nuclear medicine (v)	Negative	2	6	Yes	NR	NR	21–24
Laboratory, pathology (v)	Negative	2	6	Yes	NR	NR	21–24
Laboratory, serology (v)	Negative	2	6	Yes	NR	NR	21–24
Laboratory, sterilizing	Negative	2	10	Yes	NR	NR	21–24
Laboratory, media transfer (v)	Positive	2	4	NR	NR	NR	21–24
Nonrefrigerated body-holding room (h)	Negative	NR	10	Yes	No	NR	21–24
Autopsy room (n)	Negative	2	12	Yes	No	NR	20–24
Pharmacy (b)	Positive	2	4	NR	NR	NR	NR
Examination room	NR	2	6	NR	NR	max 60	21–24
Medication room	NR	2	4	NR	NR	max 60	21–24
Gastrointestinal endoscopy procedure room (x)	NR	2	6	NR	No	20–60	20–23
Endoscope cleaning	Negative	2	10	Yes	No	NR	NR
Treatment room (x)	NR	2	6	NR	NR	max 60	21–24
Hydrotherapy	Negative	2	6	NR	NR	NR	22–27
Physical therapy	Negative	2	6	NR	NR	Max 65	22–27
Dialysis treatment area	NR	2	6	NR	NR	NR	22–26
Dialyzer reprocessing room	Negative	NR	10	Yes	No	NR	NR
Nuclear medicine hot lab	Negative	NR	6	Yes	No	NR	21–24
Nuclear medicine treatment room	Negative	2	6	Yes	NR	NR	21–24
STERILIZING							
Sterilizer equipment room	Negative	NR	10	Yes	No	NR	NR
CENTRAL MEDICAL AND SURGICAL SUPPLY							
Soiled or decontamination room	Negative	2	6	Yes	No	NR	22–26
Clean workroom	Positive	2	4	NR	No	max 60	22–26
Sterile storage	Positive	2	4	NR	NR	max 60	22–26
SERVICE							
Food preparation center (i)	NR	2	10	NR	No	NR	22–26
Warewashing	Negative	NR	10	Yes	No	NR	NR
Dietary storage	NR	NR	2	NR	No	NR	22–26
Laundry, general	Negative	2	10	Yes	No	NR	NR
Soiled linen sorting and storage	Negative	NR	10	Yes	No	NR	NR
Clean linen storage	Positive	NR	2	NR	NR	NR	22–26
Linen and trash chute room	Negative	NR	10	Yes	No	NR	NR
Bedpan room	Negative	NR	10	Yes	No	NR	NR
Bathroom	Negative	NR	10	Yes	No	NR	22–26
Janitor's closet	Negative	NR	10	Yes	No	NR	NR
SUPPORT SPACE							
Soiled workroom or soiled holding	Negative	2	10	Yes	No	NR	NR
Clean workroom or clean holding	Positive	2	4	NR	NR	NR	NR
Hazardous material storage	Negative	2	10	Yes	No	NR	NR

Note: NR = no requirement

Operation and Maintenance

Provide an O&M manual together with final system design drawings, updated and maintained on site.

Table 12.10 Minimum Maintenance Activity and Frequency for Ventilation System Equipment and Associated Components
[Std 62.1-2016, Tbl 8.2]

Inspection/Maintenance Task	Frequency*
a. Investigate system for water intrusion or accumulation. Rectify as necessary.	As necessary
b. Verify that the space provided for routine maintenance and inspection of open cooling tower water systems, closed cooling tower water systems, and evaporative condensers is unobstructed.	Monthly
c. Open cooling tower water systems, closed cooling tower water systems, and evaporative condensers shall be treated to limit the growth of microbiological contaminants, including *legionella sp.*	Monthly
d. Verify that the space provided for routine maintenance and inspection of equipment and components is unobstructed.	Quarterly
e. Check pressure drop and scheduled replacement date of filters and air-cleaning devices. Clean or replace as necessary to ensure proper operation.	Quarterly
f. Check ultraviolet lamp. Clean or replace as needed to ensure proper operation.	Quarterly
g. Visually inspect dehumidification and humidification devices. Clean and maintain to limit fouling and microbial growth. Measure relative humidity and adjust system controls as necessary.	Quarterly
h. Maintain floor drains and trap primer located in air plenums or rooms that serve as air plenums to prevent transport of contaminants from the floor drain to the plenum.	Semiannually
i. Check ventilation and indoor air quality related control systems and devices for proper operation. Clean, lubricate, repair, adjust, or replace as needed to ensure proper operation.	Semiannually
j. Check P-traps in floor drains located in plenums or rooms that serve as air plenums. Prime as needed to ensure proper operation.	Semiannually
k. Check fan belt tension. Check for belt wear and replace if necessary to ensure proper operation. Check sheaves for evidence of improper alignment or evidence of wear and correct as needed.	Semiannually
l. Check variable-frequency drive for proper operation. Correct as needed.	Semiannually
m. Check for proper operation of cooling or heating coil for damage or evidence of leaks. Clean, restore, or replace as required.	Semiannually
n. Visually inspect outdoor air intake louvers, bird screens, mist eliminators, and adjacent areas for cleanliness and integrity; clean as needed; remove all visible debris or visible biological material observed and repair physical damage to louvers, screens, or mist eliminators if such damage impairs the item from providing the required outdoor air entry.	Semiannually
o. Visually inspect natural ventilation openings and adjacent areas for cleanliness and integrity; clean as needed. Remove all visible debris or visible biological material observed and repair physical damage to louvers, and screens if such damage impairs the item from providing the required outdoor air entry. Manual and/or automatic opening apparatus shall be physically tested for proper operation and repaired or replaced as necessary.	Semiannually

Table 12.10 Minimum Maintenance Activity and Frequency for Ventilation System Equipment and Associated Components
[Std 62.1-2016, Tbl 8.2] ***(Continued)***

Inspection/Maintenance Task	Frequency*
p. Verify the operation of the outdoor air ventilation system and any dynamic minimum outdoor air controls.	Annually
q. Check air filter fit and housing seal integrity. Correct as needed.	Annually
r. Check control box for dirt, debris, and/or loose terminations. Clean and tighten as needed.	Annually
s. Check motor contactor for pitting or other signs of damage. Repair or replace as needed.	Annually
t. Check fan blades and fan housing. Clean, repair, or replace as needed to ensure proper operation.	Annually
u. Check integrity of all panels on equipment. Replace fasteners as needed to ensure proper integrity and fit/finish of equipment.	Annually
v. Assess field serviceable bearings. Lubricate if necessary.	Annually
w. Check drain pans, drain lines, and coils for biological growth. Check adjacent areas for evidence of unintended wetting. Repair and clean as needed.	Annually
x. Check for evidence of buildup or fouling on heat exchange surfaces. Restore as needed to ensure proper operation.	Annually
y. Inspect unit for evidence of moisture carryover from cooling coils beyond the drain pan. Make corrections or repairs as necessary.	Annually
z. Check for proper damper operation. Clean, lubricate, repair, replace, or adjust as needed to ensure proper operation.	Annually
aa. Visually inspect areas of moisture accumulation for biological growth. If present, clean or disinfect as needed.	Annually
ab. Check condensate pump. Clean or replace as needed.	Annually
ac. Visually inspect exposed ductwork and external piping for insulation and vapor barrier for integrity. Correct as needed.	Annually
ad. Verify the accuracy of permanently mounted sensors whose primary function is outdoor air delivery monitoring, outdoor air delivery verification, or dynamic minimum outdoor air control, such as flow stations at an air handler and those used for demand-control ventilation. A sensor failing to meet the accuracy specified in the O&M manual shall be recalibrated or replaced. Performance verification shall include output comparison to a measurement reference standard consistent with those specified for similar devices in ASHRAE Standard 41.2 or ASHRAE Standard 111.	5 years
ae. Verify the total quantity of outdoor air delivered by air handlers set to minimum outdoor air mode. If measured minimum airflow rates are less than the design minimum rate documented in the O&M manual, ± a 10% balancing tolerance, (1) confirm the measured rate does not conform with the provisions of this standard and (2) adjust or modify the air-handler components to correct the airflow deficiency. Ventilation systems shall be balanced in accordance with ASHRAE Standard 111 or its equivalent, at least to the extent necessary to verify conformance with the total outdoor airflow and space supply airflow requirements of this standard. **Exception:** Units under 1000 L/s of supply air are exempt from this requirement.	5 years

* Minimum frequencies may be increased or decreased if indicated in the O&M manual.

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13. ENERGY-CONSERVING DESIGN

Sustainability

Recognition of the impact of the building industry's activities on the earth's ecosystem is changing the way it approaches the design, construction, operation, maintenance, reuse, and demolition of what it creates—namely addressing the environmental and long-term economic consequences of its actions. While this *sustainable design* ethic—or *sustainability*—covers things beyond the purview of HVAC&R, design for the efficient use of energy resources is a key element of sustainable design.

The basic approach to energy-efficient design is reducing loads and required power, improving transport systems, and providing efficient components and "intelligent" controls. This includes understanding the relationship between energy and power, maintaining simplicity, using self-imposed budgets, and applying energy-smart design practices.

An example of a budget designers have set for themselves for office buildings in a typical mid-USA climate:

Installed lighting	9 W/m^2	Thermal power	70 W/m^2
Space sensible cooling	45 W/m^2	Hydronic system head	180 kPa
Space heating load	30 W/m^2	Water chiller (water-cooled)	0.14 kWe/kW
Fan system pressure	0.75 kPa	Chilled-water auxiliaries	0.035 kWe/kW
Air circulation	5 L/s·m^2	Annual electric energy	160 kW/m^2·y
Overall electric power	30 W/m^2	Annual thermal energy	30 W/m^2·y·°C·day

Then, as design proceeds, compare with budget:

1. Minimize impact of building's functional requirements—to reduce, redistribute, or shift (delay) loads.
2. Minimize loads—look at peak and part-load operation.
3. Maximize subsystem efficiency—including opportunities to reclaim, redistribute, and store energy for future use.
4. Study alternative ways to integrate subsystems into the building—use easily understood design solutions to foster simplicity of operation.

HVAC&R System Design

- Consider separate systems to serve areas expected to operate on widely different schedules or design conditions.
- Arrange systems so spaces with relatively constant and weather-independent loads are served by systems separate from systems serving perimeter spaces.
- Sequence supply of cooling and heating to prevent simultaneous operation of heating and cooling systems to the same space.
- Provide controls to allow operation in an occupied mode and an unoccupied mode.
- Where diurnal temperature swings and humidity levels permit, consider coupling air distribution and building mass to allow nighttime cooling to reduce requirement of daytime mechanical cooling.
- Where climate allows, consider mixed-mode systems of HVAC and natural ventilation.
- Select energy conversion devices matched to load increments.
- Select the most efficient equipment practical at both design and part-load operating conditions.
- Seriously consider life-cycle purchasing technique for large power devices.
- Transport energy by the most energy-efficient means.
- Provide intelligent control system that provides information to operators and managers.

Summary

In designing HVAC&R systems, the need to address immediate issues such as economics, performance, and space constraints should not prevent designers from fully considering different energy sources. Consider the viability and dependability of energy resources for the long-term operation of the building. Energy standards and legislation represent only the minimum that can be achieved; strive to better utilize energy.

Energy Efficiency Standards

ANSI/ASHRAE/IES Standard 90.1-2016, *Energy Standard for Buildings Except Low-Rise Residential Buildings*

The standard includes minimum energy efficiency requirements for new buildings or portions of buildings and their systems; new systems and equipment in existing buildings.

There is a strong move to provide considerably more energy savings than required by this standard. The standard has had frequent addenda and is revised every three years.

Prescriptive Path for Compliance Highlights

Section 5. Building Envelope: Tables in the standard cover nine climate zones (see Figure 13.1) for nonresidential, residential, and semiheated occupancies for minimum allowable insulating value of envelope elements and maximum allowable solar heat gain of fenestration.

Section 6. HVAC; minimum equipment efficiencies. Required controls. Allowable fan power for supply air systems. Hydronic systems pump power. Heat rejection equipment fans. Exhaust energy recovery. Heat recovery systems for service water heating systems. Radiant heating for unenclosed spaces.

Section 7. Service water heating—minimum equipment efficiencies.

Section 8. Power: Feeder conductors sized for maximum voltage drop of 2% at design load; branch circuit conductors 3%.

Section 9. Lighting: Limitations on lighting power densities, controls required.

Section 10. Other equipment: Minimum allowable electric motor efficiencies.

Normative Appendix A. Rated R-value of insulation and assembly U-factor, C-factor, and F-factor determinations.

Normative Appendix C. Methodology for building envelope trade-off option in Section 5.6.

Alternative to Prescriptive Methods of Compliance

Section 11. Energy cost budget method.

Normative Appendix G. Performance rating method.

ASHRAE Standard 90.2-2007, *Energy Efficient Design of Low-Rise Residential Buildings*

Prescriptive minimum requirements for envelope and equipment with alternate annual energy cost method of compliance.

ASHRAE Standard 100-2006, *Energy Conservation in Existing Buildings*

A building or a complex of buildings complies when the following requirements have been met and recorded on Form A of the standard and the party determining compliance has (1) conducted an energy survey as required by the standard in Section 5, (2) stated in writing that the operation and maintenance requirements in Section 5 have been met, and (3) has stated in writing that building and equipment modifications in Section 7 have been met.

More stringent and more detailed requirements can be expected in future editions of the standard.

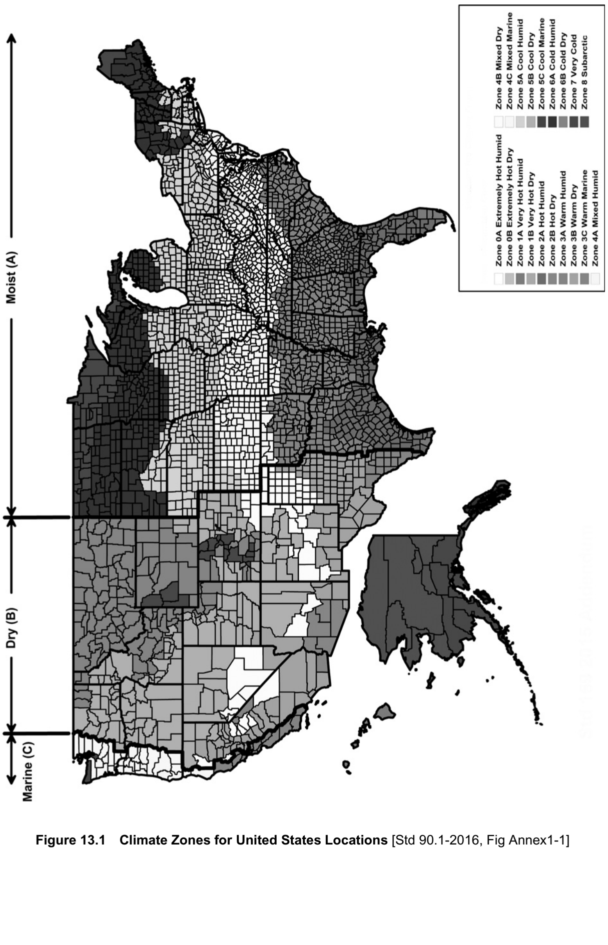
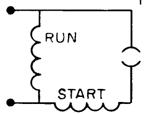
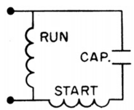
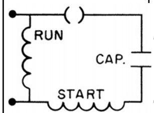
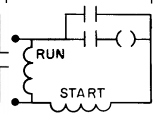
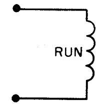
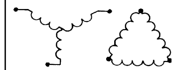
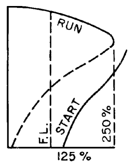
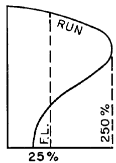
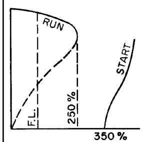
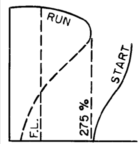
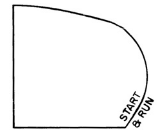


Figure 13.1 Climate Zones for United States Locations [Std 90.1-2016, Fig Annex1-1]

Table 14.1 Characteristics of AC Motors (Nonhermetic) [2016S, Ch 45, Tbl 4]

	Split-Phase	Permanent Split-Capacitor	Capacitor-Start Induction-Run	Capacitor-Start Capacitor-Run	Shaded-Pole	Polyphase, 60-Hz
Connection Diagram						
Speed Torque Curves						
Starting Method	Centrifugal switch	None	Centrifugal switch	Centrifugal switch	None	Motor controller
Ratings, kW	0.04 to 0.4	0.04 to 3.7	0.04 to 3.7	0.04 to 3.7	0.04 to 0.19	0.4 and up
Full-Load Speeds at 60-Hz (Two-Pole, Four-Pole)	3450 to 1725	3450 to 1725	3450 to 1725	3500 to 1750	3100 to 1550	3500 to 1750
Torque[a] **Locked Rotor** **Breakdown**	 125 to 150% 250 to 300%	 25% 250 to 300%	 250 to 350% 250 to 300%	 250% 250%	 25% 125%	 150 to 350% 250 to 350%
Speed Classification	Constant	Constant	Constant	Constant	Constant or adjustable	Constant
Full-Load Power Factor	60%	95%	65%	95%	60%	80%
Efficiency	Medium	High	Medium	High	Low	High-Medium

[a] Expressed as percent of rated horsepower torque.

Table 14.2 Motor Full-Load Amperes

Nominal Power, kW	Recommended Starter Size Three Phase		Three-Phase AC Squirrel-Cage and Wound-Rotor (Induction Type)			Recommended Starter Size Single Phase	Single-Phase AC			Nominal Power, kW
	230 V	460 V	200 V	230 V	460 V	230 V	115 V	200 V	230 V	
0.12						00	4.4	2.5	2.2	0.12
0.19						00	5.8	3.3	2.9	0.19
0.37	00	00	2.3	2	1	00	9.8	5.6	4.9	0.37
0.56	00	00	3.2	2.8	1.4	00	13.8	7.9	6.9	0.56
0.75	00	00	4.1	3.6	1.8	00	16	9.2	8	0.75
1.12	00	00	6.0	5.2	2.6	0	20	11.5	10	1.12
1.5	0	00	7.8	6.8	3.4	0	24	13.8	12	1.5
2.2	0	0	11.0	9.6	4.8	1	34	19.6	17	2.2
3.7	1	0	17.5	15.2	7.6	1	56	32.2	28	3.7
5.6	1	1	25.3	22	11	2	80	46	40	5.6
7.5	2	1	32.2	28	14	2	100	57.5	50	7.5
11	2	2	48.3	42	21	3				11
15	3	2	62.1	54	27					15
19	3	2	78.2	68	34					19
22	3	3	92	80	40					22
30	4	3	119.6	104	52					30
37	4	3	149.5	130	65					37
45	5	4	177.1	154	77					45
56	5	4	220.8	192	96					56
75	5	4	285.2	248	124					75
93	6	5	358.8	312	156					93
112	6	5	414	360	180					112
150	6	5	552	480	240					150

Values are for motors with normal torque characteristics running at usual belted speeds.

Table 14.3 Useful Electrical Formulas

To Find	Direct Current	Single Phase	Three Phase
Amperes when power known	$1000P\eta$	$\frac{1000P}{(\eta F)}$	$\frac{1000P}{(1.73\eta F)}$
Amperes when kVA known	—	1000 kVA/η	1000 kVA/(1.73η)
kVA	—	IE/1000	1.73 IE/1000
Power out, kW	ηIE/1000	ηIEF/1000	1. 73 ηIEF/1000

I = amperes; *E* = volts; η = efficiency expressed as decimal; *F* = power factor; *P* = kilowatts; kVA = kilovolt-amperes.

Motor Controllers

Three-phase constant-speed induction motor controllers are usually full-voltage except when the starting current must be reduced in larger motors to meet power system limitations; such motor controllers may be of various row types. All are used for starting and stopping the motor and include overcurrent protection.

Variable-Speed Drives (VSDs)

By far the most energy-efficient means of varying flow of fans and pumps driven by electric motors are VSDs. Their application involves careful consideration of their effects (here VSD is considered synonymous with variable-frequency drive [VFD], pulse-width modulated drive [PWM drive], adjustable-speed drive [ASD], and adjustable-frequency drive [AFD].) A VSD consists of a pulse-width-modulation controller with insulated-gate bipolar transistors (IGBTs) and an induction motor. The IGBT changes the characteristics of waveforms applied to a motor due to the speed at which the IGBT cycles on and off. At switching speed up to 20 k Hz, the impedance in the connecting cable is far less than the motor impedance, particularly for small motors, causing pulse reflectance at the motor terminals to form damaging high voltage. NEMA motor standard MG1 states PWM drive limits and establishes a peak of 1600 V and a minimum rise time of 0.1 μs for motors rated less than 600 V. Typical manufacturer maximum voltage withstand levels range from 1000 V to 1800 V. When specifying motors for operation on VSDs, the voltage withstand level based on the dV/dt of the drive and the known cable distance should be specified.

Harmonics caused by the portion of a VSD converting line power LDC affect input lines and are termed *line-side harmonics*. Output line harmonics are caused solely by the inverter section of the VSD and are known as load side or motor harmonics. Generally, PWM drives containing internal bus reaction or three-phase AC line reactors do not cause interference with other electrical equipment. There may be problems when a VSD is switched onto a standby generator, or when power factor correction capacitors are used.

15. FUELS AND COMBUSTION

Table 15.1 Maximum Capacity of Gas Pipe in Litres per Second [2017F, Ch 22, Tbl 40]
(At gas pressures of 3.5 kPa above atm. or less and a pressure drop of 75 Pa. Density = 0.735 kg/m^3)

Nominal Iron Pipe Size, mm	Internal Diameter, mm	Length of Pipe, m													
		10	20	30	40	50	60	70	80	90	100	125	150	175	200
8	9.25	0.19	0.13	0.11	0.09	0.08	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.19	0.13
10	12.52	0.43	0.29	0.24	0.20	0.18	0.16	0.15	0.14	0.13	0.12	0.12	0.11	0.43	0.29
15	15.80	0.79	0.54	0.44	0.37	0.33	0.30	0.28	0.26	0.24	0.23	0.22	0.21	0.79	0.54
20	20.93	1.65	1.13	0.91	0.78	0.69	0.63	0.58	0.54	0.50	0.47	0.45	0.43	1.65	1.13
25	26.14	2.95	2.03	1.63	1.40	1.24	1.12	1.03	0.96	0.90	0.85	0.81	0.77	2.95	2.03
32	35.05	6.4	4.4	3.5	3.0	2.7	2.4	2.2	2.1	1.9	1.8	1.7	1.7	6.4	4.4
40	40.89	9.6	6.6	5.3	4.5	4.0	3.6	3.3	3.1	2.9	2.8	2.6	2.5	9.6	6.6
50	52.50	18.4	12.7	10.2	8.7	7.7	7.0	6.4	6.0	5.6	5.3	5.0	4.8	18.4	12.7
65	62.71	29.3	20.2	16.2	13.9	12.3	11.1	10.2	9.5	8.9	8.4	8.0	7.7	29.3	20.2
80	77.93	51.9	35.7	28.6	24.5	21.7	19.7	18.1	16.8	15.8	14.9	14.2	13.5	51.9	35.7
100	102.26	105.8	72.7	58.4	50.0	44.3	40.1	36.9	34.4	32.2	30.4	28.9	27.6	105.8	72.7

Note: Capacity is in litres per second at gas pressures of 3.5 kPa (gage) or less and a pressure drop of 75 kPa; density = 0.735 kg/m^3.

Table 15.2 Typical API Gravity, Density, and Heating Value of Standard Grades of Fuel Oil [2017F, Ch 28, Tbl 10]

Grade No.	Density, kg/m^3	Heating Value, GJ/m^3
1	833 to 800	38.2 to 37.0
2	874 to 834	39.5 to 38.2
4	933 to 886	41.3 to 39.9
5L	951 to 921	41.8 to 40.9
5H	968 to 945	42.4 to 41.6
6	1012 to 965	43.5 to 42.2

Types of Fuel Oils

Fuel oils for heating are broadly classified as distillate fuel oils (lighter oils) or residual fuel oils (heavier oils). ASTM has established specifications for fuel oil properties which subdivide the oils into various grades. Grades No. 1 and 2 are distillate fuel oils. Grades 4,5 (Light), 5 (Heavy), and 6 are residual fuel oils. Specifications for the grades are based on required characteristics of fuel oils for use in different types of burners. The ANSI standard specification for fuel oils is ASTM Standard D396.

Grade No. 1 is a light distillate intended for vaporizing-type burners. High volatility is essential to continued evaporation of the fuel oil with minimum residue.

Grade No. 2 is a heavier (API Gravity) distillate than No. 1. It is used primarily with pressure-atomizing (gun) burners that spray the oil into a combustion chamber. The atomized oil vapor mixed with air and burns. This grade is used in most domestic burners and many medium capacity commercial-industrial burners.

Grade No. 4 is an intermediate fuel that is considered either a light residual or a heavy distillate. Intended for burners that atomize oils of higher viscosity than domestic burners can handle, its permissible viscosity range allows it to be pumped and atomized at relatively low storage temperatures.

Grade No. 5 (Light) is a residual fuel of intermediate viscosity for burners that handle fuel more viscous than No. 4 without preheating. Preheating may be necessary in some equipment for burning and, in colder climates, for handling.

Grade No. 5 (Heavy) is a residual fuel more viscous than No. 5 (Light), but intended for similar purposes. Preheating is usually necessary for burning and, in colder climates, for handling.

Grade No. 6, sometimes referred to as Bunker C, is a high-viscosity oil used mostly in commercial and industrial heating. It requires preheating in the storage tank to permit pumping, and additional preheating at the burner to permit atomizing.

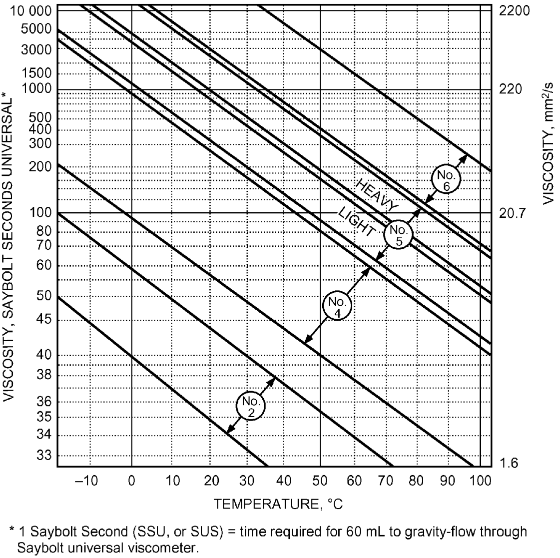


Figure 15.1 Approximate Viscosity of Fuel Oils [2017F, Ch 28, Fig 2]

Types and Properties of Liquid Fuels for Engines

The primary stationary engine fuels are diesel and gas turbine oils, natural gases, and liquefied petroleum gases. Other fuels include sewage gas, manufactured gas, and gas mixtures. Gasoline and the JP series of gas turbine fuels are rarely used for stationary engines.

Properties of the three grades of diesel fuel oils (1-D, 2-D, and 4-D) are listed in ASTM Standard D975.

Grade No. 2-D includes the class of lower volatility distillate gas oils. These fuels are used in high-speed engines with relatively high loads and uniform speeds, or in engines not requiring fuels with the higher volatility or other properties specified for Grade No. 1-D.

Grade No. 4-D covers the class of more viscous distillates and blends of these distillates with residual fuel oils. These fuels are used in low- and medium-speed engines involving sustained loads at essentially constant speed.

Property specifications and test methods for Grade No. 1-D, 2-D, and 4-D diesel fuel oils are essentially identical to specifications of Grade No. 1, 2, and 4 fuel oils, respectively. However, diesel fuel oils have an additional specification for **cetane number**, which measures ignition quality and influences combustion roughness. Cetane number requirements depend on engine design, size, speed and load variations, and starting and atmospheric conditions. An increase in cetane number over values actually required does not improve engine performance. Thus, the cetane number should be as low as possible to assure maximum fuel availability. ASTM Standard D975 provides several methods for estimating cetane number from other fuel oil properties.

ASTM Standard D2880 for gas turbine fuel oils relates gas turbine fuel oil grades to fuel and diesel fuel oil grades.

Table 15.3 Approximate Air Requirements for Stoichiometric Combustion of Various Fuels [2017F, Ch 28, Tbl 13]

Type of Fuel	Theoretical Air Required for Combustion
Solid fuels	kg/kg fuel
Anthracite	9.6
Semibituminous	11.2
Bituminous	10.3
Lignite	6.2
Coke	11.2
Liquid fuels	Mg/m^3 fuel
No. 1 fuel oil	12.34
No. 2 fuel oil	12.70
No. 5 fuel oil	13.42
No. 6 fuel oil	13.66
Gaseous fuels	m^3/m^3 fuel
Natural gas	9.6
Butane	31.1
Propane	24.0

Table 15.4 Approximate Maximum Theoretical (Stoichiometric) CO_2 Values and CO_2 Values of Various Fuels with Different Percentages of Excess Air [2017F, Ch 28, Tbl 13]

Type of Fuel	Theoretical or Maximum CO_2, %	Percent CO_2 at Given Excess Air Values		
		20%	40%	60%
Gaseous Fuels				
Natural gas	12.1	9.9	8.4	7.3
Propane gas (commercial)	13.9	11.4	9.6	8.4
Butane gas (commercial)	14.1	11.6	9.8	8.5
Mixed gas (natural and carbureted water gas)	11.2	12.5	10.5	9.1
Carbureted water gas	17.2	14.2	12.1	10.6
Coke oven gas	11.2	9.2	7.8	6.8
Liquid Fuels				
No. 1 and 2 fuel oil	15.0	12.3	10.5	9.1
No. 6 fuel oil	16.5	13.6	11.6	10.1
Solid Fuels				
Bituminous coal	18.2	15.1	12.9	11.3
Anthracite	20.2	16.8	14.4	12.6
Coke	21.0	17.5	15.0	13.0

Table 15.5 Recommended Nominal Size for Fuel Oil Suction Lines from Tank to Pump (Distillate Grades No. 1 and No. 2) [2017F, Ch 22, Tbl 42]

Pumping Rate, L/h	Length of Run in Metres at Maximum Suction Lift of 9.0 kPa									
	10	20	30	40	50	60	70	80	90	100
50	15	15	15	15	15	20	20	20	25	25
100	15	15	15	15	20	20	20	20	25	25
200	15	20	20	20	20	20	25	25	25	25
300	15	20	20	20	20	25	25	25	25	32
400	20	20	20	20	25	25	25	25	32	32
500	20	25	25	25	25	25	32	32	32	32
600	20	25	25	25	25	32	32	32	32	50
700	20	25	25	25	25	32	32	32	50	50
800	20	25	25	25	32	32	32	32	50	50

Note: Sizes (in millimetres) are nominal.

16. OWNING AND OPERATING

Maintenance Costs

The maintenance cost of mechanical systems varies widely depending on configuration, equipment locations, accessibility, system complexity, service duty, geography, and system reliability requirements.

Dohrmann and Alereza (1986) obtained maintenance costs and HVAC system information from 342 buildings located in 35 states in the United States. In 1983 U.S. dollars, data collected showed a mean HVAC system maintenance cost of $3.40/m^2 per year, with a median cost of $2.60/m^2 per year. Building age has a statistically significant but minor effect on HVAC maintenance costs. Analysis also indicated that building size is not statistically significant in explaining cost variation. The type of maintenance program or service agency that building management chooses can also have a significant effect on total HVAC maintenance costs. Although extensive or thorough routine and preventive maintenance programs cost more to administer, they usually extend equipment life; improve reliability; and reduce system downtime, energy costs, and overall life-cycle costs.

Some maintenance cost data are available, both in the public domain and from proprietary sources used by various commercial service providers. These sources may include equipment manufacturers, independent service providers, insurers, government agencies (e.g., the U.S. General Services Administration), and industry-related organizations [e.g., the Building Owners and Managers Association (BOMA)] and service industry publications. More traditional, widely used products and components are likely to have statistically reliable records. However, design changes or modifications necessitated by industry changes, such as alternative refrigerants, may make historical data less relevant.

Newer HVAC products, components, system configurations, control systems and protocols, and upgraded or revised system applications present an additional challenge. Care is required when using data not drawn from broad experience or field reports. In many cases, maintenance information is proprietary or was sponsored by a particular entity or group. Particular care should be taken when using such data. It is the user’s responsibility to obtain these data and to determine their appropriateness and suitability for the application being considered.

ASHRAE research project TRP-1237 (Abramson et al. 2005) developed a standardized Internet-based data collection tool and database on HVAC equipment service life and maintenance costs. The database was seeded with data on 163 buildings from around the country. Maintenance cost data were gathered for total HVAC system maintenance costs from 100 facilities. In 2004 dollars, the mean HVAC maintenance cost from these data was $5.06/m^2, and the median cost was $4.74/m^2. Table 16.1 compares these figures with estimates reported by Dohrmann and Alereza (1986), both in terms of contemporary dollars, and in 2004 dollars, and shows that the cost per square metre varies widely between studies.

Estimating Maintenance Costs

Total HVAC maintenance cost for new and existing buildings with various types of equipment may be estimated several ways, using several resources. Equipment maintenance requirements can be obtained from the equipment manufacturers for large or custom pieces of equipment. Estimating in-house labor requirements can be difficult; BOMA provides guidance on this topic. Many independent mechanical service companies provide preventative maintenance contracts. These firms typically have proprietary estimating programs developed through their experience, and often provide generalized maintenance costs to engineers and owners upon request, without obligation.

Table 16.1 Comparison of Maintenance Costs Between Studies
[2015A, Ch 37, Tbl 6]

Survey	Cost per m^2, as Reported		Consumer Price Index	Cost per m^2, 2004 Dollars	
	Mean	Median		Mean	Median
Dohrmann and Alereza (1986)	$3.44	$2.58	99.6	$6.57	$4.95
Abramson et al. (2005)	$5.06	$4.74	188.9	$5.06	$4.74

When evaluating various HVAC systems during design or retrofit, the absolute magnitude of maintenance costs may not be as important as the relative costs. Whichever estimating method or resource is selected, it should be used consistently throughout any evaluation. Mixing information from different resources in an evaluation may provide erroneous results.

Applying simple costs per unit of building floor area for maintenance is highly discouraged. Maintenance costs can be generalized by system types. When projecting maintenance costs for different HVAC systems, the major system components need to be identified with a required level of maintenance. The potential long-term costs of environmental issues on maintenance costs should also be considered.

Table 16.2 Owning and Operating Cost Data and Summary [2015A, Ch 37, Tbl 1]

OWNING COSTS			
I. Initial Cost of System		_______	
II. Periodic Costs			
A. Income taxes	_______		
B. Property taxes	_______		
C. Insurance	_______		
D. Rent	_______		
E. Other periodic costs	_______		
Total Periodic Costs		_______	
III. Replacement Cost		_______	
IV. Salvage Value		_______	
Total Owning Costs			_______
OPERATING COSTS			
V. Annual Utility, Fuel, Water, etc., Costs			
A. Utilities			
1. Electricity	_______		
2. Natural gas	_______		
3. Water/sewer	_______		
4. Purchased steam	_______		
5. Purchased hot/chilled water	_______		
B. Fuels			
1. Propane	_______		
2. Fuel oil	_______		
3. Diesel	_______		
4. Coal	_______		
C. On-site generation of electricity	_______		
D. Other utility, fuel, water, etc., costs	_______		
Total		_______	
VI. Annual Maintenance Allowances/Costs			
A. In-house labor	_______		
B. Contracted maintenance service	_______		
C. In-house materials	_______		
D. Other maintenance allowances/costs (e.g., water treatment)	_______		
Total		_______	
VII. Annual Administration Costs		_______	
Total Annual Operating Costs			_______
TOTAL ANNUAL OWNING AND OPERATING COSTS			_______

Simple Payback

This ignores inflation and the time value of money. The annual revenue stream cost savings and other factors are estimated and divided into the initial capital outlay; the result is the simple payback time in years.

Life-Cycle Costs

A representation in present dollars of the cost of an investment over its lifetime is useful for evaluating mutually exclusive alternatives that have the same anticipated lifetime.

A *discount rate* is required for a life-cycle-cost calculation. The discount rate represents the cost of capital to building owners. In essence, it is the rate on a loan (or bond) adjusted to account for inflation and taxes. A 3% real discount rate is typical for energy policy analyses. Higher rates are often used by private investors for economic evaluation of commercial construction. To account for inflation and fuel escalation, either lower the discount rate or inflate future energy and maintenance costs.

Life-cycle cost is calculated by determining the present worth of the cost of an investment. For system alternatives, it is

$$\text{LCC} = \text{IC} + \text{ESPWF}(\text{COST}_{energy} + \text{COST}_{maint}) \tag{16.1}$$

where

LCC = life-cycle cost

IC = initial cost premium of alternative

ESPWF = equal series present worth factor (see Table 16.3)

COST_{energy} = yearly energy cost saving

COST_{maint} = yearly maintenance cost reduction

ESPWF for other lifetimes and discount rates can be calculated from

$$\text{ESPWF} = \frac{(1+d)^n - 1}{d(1+d)^n} \tag{16.2}$$

where n = lifetime in years and d = discount rate in percent/100.

Note that ESPWF can only be used when annual costs remain constant.

Capital Recovery Factors

The future equal payments to repay a present value of money is determined by the capital recovery factor, which is the reciprocal of the present worth factor for a series of equal payments.

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} = \frac{i}{1-(1+i)^n} \tag{16.3}$$

where i is the compound interest rate.

Improved Payback Analysis

Similar to simple payback but cost of money is considered.

$$n = \frac{\ln[\text{CRF}/(i - \text{CRF})]}{\ln(1+i)} \tag{16.4}$$

Table 16.3 Equal Series Present Worth Factors (ESPWFs)

Lifetime (years)	Discount Rate							
	2.5%	3.0%	3.5%	4.0%	4.5%	7%	10%	15%
7	6.35	6.23	6.11	6.00	5.89	5.39	4.8	4.16
10	8.75	8.53	8.32	8.11	7.91	7.02	6.14	5.02
15	12.38	11.94	11.52	11.12	10.74	9.11	7.61	5.85

Table 16.4 Annual Capital Recovery Factors [2003A, Ch 36, Tbl 5]

Years	Rate of Return or Interest Rate, % per Year				
	3.5	4.5	6	8	10
2	0.526 40	0.534 00	0.545 44	0.560 77	0.576 19
4	0.272 25	0.278 74	0.288 59	0.301 92	0.315 47
6	0.187 67	0.193 88	0.203 36	0.216 32	0.229 61
8	0.145 48	0.151 61	0.161 04	0.174 01	0.187 44
10	0.120 24	0.126 38	0.135 87	0.149 03	0.162 75
12	0.103 48	0.109 67	0.119 28	0.132 70	0.146 76
14	0.091 57	0.097 82	0.107 58	0.121 30	0.135 75
16	0.082 68	0.089 02	0.098 95	0.112 98	0.127 82
18	0.075 82	0.082 24	0.092 36	0.106 70	0.121 93

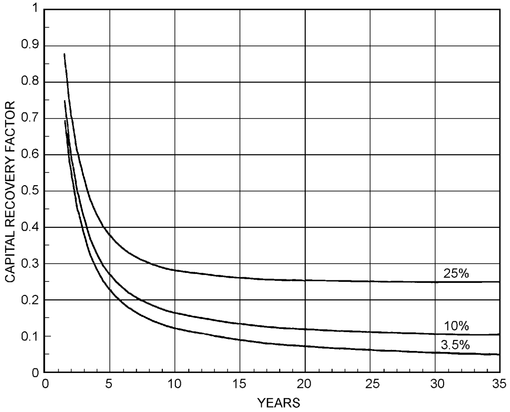


Figure 16.1 Capital Recovery Factor Versus Time [2003A, Ch 36, Fig 1]

17. SOUND

Sound Pressure and Sound Pressure Level

Sound intensity is difficult to measure directly, but sound pressure is relatively easy to measure; the human ear and microphones are pressure-sensitive devices. A decibel scale for sound pressure can be created in a manner analogous to the decibel scale for sound intensity, with a reference pressure of 20 μPa, which corresponds to the approximate threshold of hearing. Because pressure squared is proportional to intensity, sound pressure level is

$$L_p = 10\ \log(p/p_{ref})^2 \text{ re } p_{ref} \tag{17.1}$$

Because p/p_{ref} is 20 μPa, which is 2×10^{-5} Pa, and since $10\ \log p^2 = 20\ \log p$,

$$L_p = 20\ \log(p/2 \times 10^{-5}) \text{ re } 20\ \mu\text{Pa} \tag{17.2}$$

where p is the root mean square (rms) value of pressure in micropascals. Or

$$L_p = 20\ \log p + 94 \text{ db re } 20\ \mu\text{Pa} \tag{17.3}$$

The human ear responds across a broad range of sound pressures. The linear range scale for sound pressure in Table 17.1 is awkward in this form; therefore, the equivalent logarithmic notations should be used.

Table 17.1 Typical Sound Pressures and Sound Pressure Levels
[2017F, Ch 8, Tbl 1]

Source	Sound Pressure, Pa	Sound Pressure Level, dB re 20 μPa	Subjective Reaction
Military jet takeoff at 30 m	200	140	Extreme danger
Artillery fire at 3 m	63.2	130	
Passenger jet takeoff at 15 m	20	120	Threshold of pain
Loud rock band	6.3	110	Threshold of discomfort
Automobile horn at 3 m	2	100	
Unmuffled large diesel engine at 40 m	0.6	90	Very loud
Accelerating diesel truck at 15 m	0.2	80	
Freight train at 30 m	0.06	70	
Conversational speech at 1 m	0.02	60	
Window air conditioner at 3 m	0.006	50	Moderate
Quiet residential area	0.002	40	
Whispered conversation at 2 m	0.0006	30	
Buzzing insect at 1 m	0.0002	20	
Threshold of good hearing	0.00006	10	Faint
Threshold of excellent youthful hearing	0.00002	0	Threshold of hearing

Combining Sound Levels

To estimate the levels from multiple sources from the levels from each source, the intensities (not the levels) must be added. Thus, the levels must first be converted to find intensities, the intensities summed, and then converted to a level again, so the combination of multiple levels L_1, L_2, etc., produces a level L_{sum} given by

$$L_{sum} = 10 \log \sum_i 10^{L_i/10} \tag{17.4}$$

where for sound pressure level (L_p), $10^{L_i/10}$ is p_i^2/p_{ref}^2, and L_i is the sound pressure level for the ith source.

A simpler and slightly less accurate method is outlined in Table 17.2. This method, although not exact, results in errors of 1 dB or less. The process with a series of levels may be shortened by combining the largest with the next largest, then combining this sum with the third largest, then the fourth largest, and so on until the combination of the remaining levels is 10 dB lower than the combined level. The process may then be stopped.

Sound Power and Sound Power Level

A fundamental characteristic of an acoustic source is its ability to radiate energy. Some energy input excites the source, which radiates some fraction of this energy in the form of sound. Since unit power radiated through a unit sphere yields unit intensity, the power reference base, established by international agreement, is 1 picowatt (pW) (10^{-12} W). The reference quantity used should be stated explicitly. A definition of sound power level is, therefore

$$L_w = \log w/(10^{-12}\text{W}) \text{ dB re 1 pW} \quad \text{or} \quad L_w = 10 \log w + 120 \text{ dB re 1 pW} \tag{17.5}$$

Table 17.2 Combining Two Sound Levels [2017F, Ch 8, Tbl 3]

Difference between levels to be combined, dB	**0 to 1**	**2 to 4**	**5 to 9**	**10 and More**
Number of decibels to add to highest level to obtain combined level	3	2	1	0

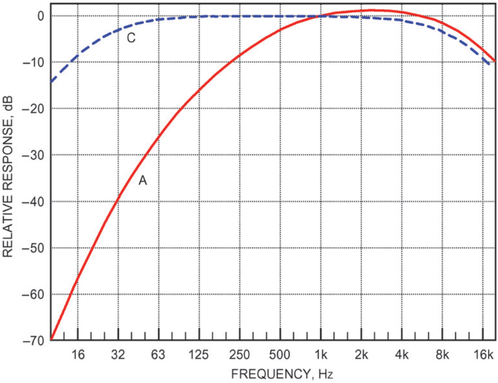


Figure 17.1 Curves Showing A- and C-Weighting Responses for Sound Level Meters
[2017F, Ch 8, Fig 1]

Table 17.3 Midband and Approximate Upper and Lower Cutoff Frequencies for Octave and 1/3 Octave Band Filters [2017F, Ch 8, Tbl 4]

Octave Bands, Hz			1/3 Octave Bands, Hz		
Lower	**Midband**	**Upper**	**Lower**	**Midband**	**Upper**
			11.2	12.5	14
11.2	16	22.4	14	16	18
			18	20	22.4
			22.4	25	28
22.4	31.5	45	28	31.5	35.5
			35.5	40	45
			45	50	56
45	63	90	56	63	71
			71	80	90
			90	100	112
90	125	180	112	125	140
			140	160	180
			180	200	224
180	250	355	224	250	280
			280	315	355
			355	400	450
355	500	710	450	500	560
			560	630	710
			710	800	900
710	1 000	1 400	900	1 000	1 120
			1 120	1 250	1 400
			1 400	1 600	1 800
1 400	2 000	2 800	1 800	2 000	2 240
			2 240	2 500	2 800
			2 800	3 150	3 550
2 800	4 000	5 600	3 550	4 000	4 500
			4 500	5 000	5 600
			5 600	6 300	7 100
5 600	8 000	11 200	7 100	8 000	9 000
			9 000	10 000	11 200
			11 200	12 500	14 000
11 200	16 000	22 400	14 000	16 000	18 000
			18 000	20 000	22 400

Table 17.4 Design Guidelines for HVAC-Related Background Sound in Rooms [2015A, Ch 48, Tbl 1]

Room Types		Octave Band Analysis[a] NC/RC[b]	Approximate Overall Sound Pressure Level[a] dBA[c]	dBC[c]
Rooms with Intrusion from Outdoor Noise Sources[d]	Traffic noise	N/A	45	70
	Aircraft flyovers	N/A	45	70
Residences, Apartments, Condominiums	Living areas	30	35	60
	Bathrooms, kitchens, utility rooms	35	40	60
Hotels/Motels	Individual rooms or suites	30	35	60
	Meeting/banquet rooms	30	35	60
	Corridors and lobbies	40	45	65
	Service/support areas	40	45	65
Office Buildings	Executive and private offices	30	35	60
	Conference rooms	30	35	60
	Teleconference rooms	25	30	55
	Open-plan offices	40	45	65
	Corridors and lobbies	40	45	65
Courtrooms	Unamplified speech	30	35	60
	Amplified speech	35	40	60
Performing Arts Spaces	Drama theaters, concert and recital halls	20	25	50
	Music teaching studios	25	30	55
	Music practice rooms	30	35	60
Hospitals and Clinics	Patient rooms	30	35	60
	Wards	35	40	60
	Operating and procedure rooms	35	40	60
	Corridors and lobbies	40	45	65
Laboratories	Testing/research w/minimal speech communication	50	55	75
	Extensive phone use and speech communication	45	50	70
	Group teaching	35	40	60
Churches, Mosques, Synagogues	General assembly with critical music programs[e]	25	30	55
Schools[f]	Classrooms	30	35	60
	Large lecture rooms with speech amplification	30	35	60
	Large lecture rooms without speech amplification	25	30	55
Libraries		30	35	60
Indoor Stadiums, Gymnasiums	Gymnasiums and natatoriums[g]	45	50	70
	Large-seating-capacity spaces with speech amplification[g]	50	55	75

N/A = Not applicable

[a]Values and ranges are based on judgment and experience, and represent general limits of acceptability for typical building occupancies.

[b]NC: this metric plots octave band sound levels against a family of reference curves, with the number rating equal to the highest tangent line value.

RC: when sound quality in the space is important, the RC metric provides a diagnostic tool to quantify both the speech interference level and spectral imbalance.

[c]dBA and dBC: these are overall sound pressure level measurements with A- and C-weighting, and serve as good references for a fast, single-number measurement. They are also appropriate for specification in cases where no octave band sound data are available for design.

[d]Intrusive noise is addressed here for use in evaluating possible non-HVAC noise that is likely to contribute to background noise levels.

[e]An experienced acoustical consultant should be retained for guidance on acoustically critical spaces (below RC 30) and for all performing arts spaces.

[f]Some educators and others believe that HVAC-related sound criteria for schools, as listed in previous editions of this table, are too high and impede learning for affected groups of all ages. See ANSI/ASA Standard S12.60 for classroom acoustics and a justification for lower sound criteria in schools. The HVAC component of total noise meets the background noise requirement of that standard if HVAC-related background sound is approximately NC/RC 25. Within this category, designs for K-8 schools should be quieter than those for high schools and colleges.

[g]RC or NC criteria for these spaces need only be selected for the desired speech and hearing conditions.

Table 17.5 Comparison of Sound Rating Methods [2015A, Ch 48, Tbl 4]

Method	Overview	Considers Speech Interference Effects	Evaluates Sound Quality	Components Presently Rated by Each Method
dBA	No quality assessment Frequently used for outdoor noise ordinances	Yes	No	Cooling towers Water chillers Condensing units
NC	Can rate components Limited quality assessment Does not evaluate low-frequency rumble	Yes	Somewhat	Air terminals Diffusers
RC Mark II	Used to evaluate systems Should not be used to evaluate components Evaluates sound quality Provides improved diagnostics capability	Yes	Yes	Not used for component rating
NCB	Can rate components Some quality assessment	Yes	Somewhat	See NC
RNC	Some quality assessment Attempts to quantify fluctuations	Yes	Somewhat	Not used for component rating

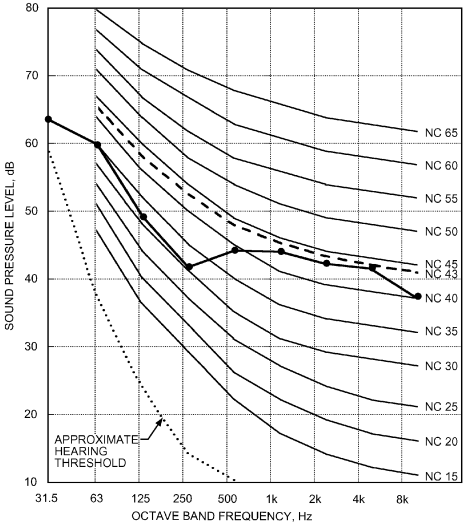
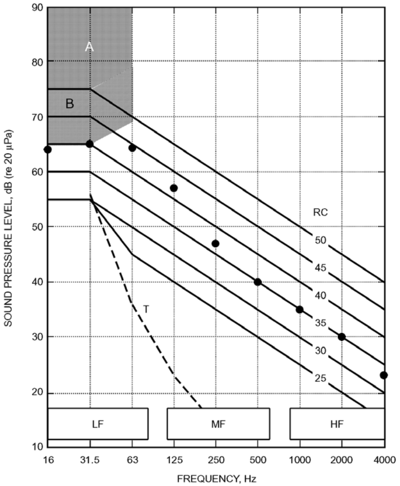


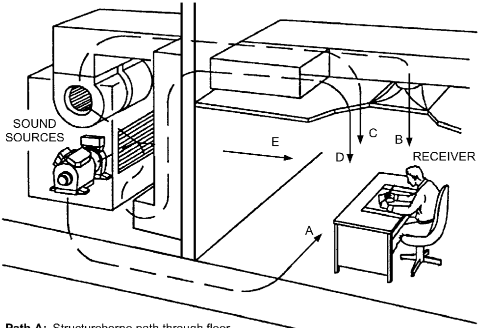
Figure 17.2 NC (Noise Criteria) Curves and Typical Spectrum (Curve with Symbols)
[2017F, Ch 8, Fig 7]

Sound



Note:
- Noise levels for lightweight wall and ceiling constructions:
  - In shaded region B are likely to generate vibration that may be perceptible. There is a slight possibility of rattles in light fixtures, doors, windows, etc.
  - In shaded region A have a high probability of generating easily perceptible noise- induced vibration. Audible rattling in light fixtures, doors, windows, etc. may be anticipated.
- Regions LF, MF, and HF are explained in the text.
- Solid dots are sound pressure levels for the example discussed in the text.

Figure 17.3 Room Criteria Curves, Mark II [2015A, Ch 48, Fig 6]



Path A: Structureborne path through floor
Path B: Airborne path through supply air system
Path C: Duct breakout from supply air duct
Path D: Airborne path through return air system
Path E: Airborne path through mechanical equipment room wall

Figure 17.4 Typical Paths of Noise and Vibration Propagation in HVAC Systems
[2015A, Ch 48, Fig 1]

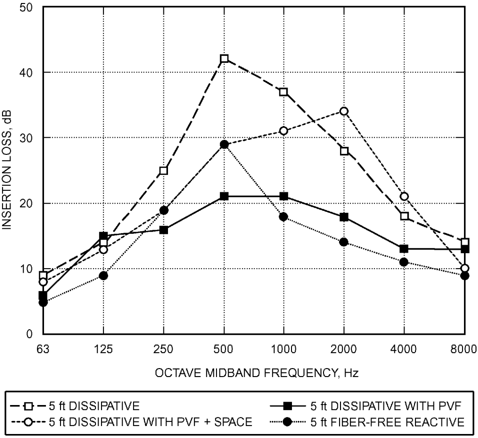
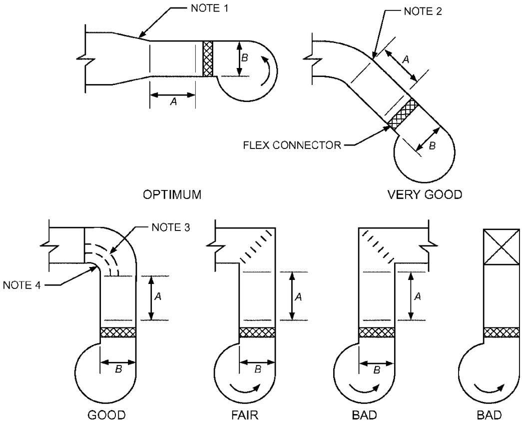


Figure 17.5 Comparison of 1.5 m Dissipative and Reactive Silencer Performance— Film Liner to Conform to NFPA 90A [2015A, Ch 48, Fig 23]



Notes:

1. Slopes of 1 in 7 preferred. Slopes of 1 in 4 permitted below 10 m/s.
2. Dimension *A* should be at least 1.5 times *B*, where *B* is largest discharge duct dimension.
3. Rugged turning vanes should extend full radius of elbow.
4. Minimum 150 mm radius required.

Figure 17.6 Various Outlet Configurations for Centrifugal Fans and Their Possible Rumble Conditions [2015A, Ch 48, Fig 25]

A number of AHRI, AMCA, CTI, and ANSI sound standards are used by equipment manufacturers to provide accurate sound data. Manufacturer-supplied data in accordance with the appropriate standard should be used in preference to any earlier empirical information in evaluating the noise resulting from a particular equipment item.

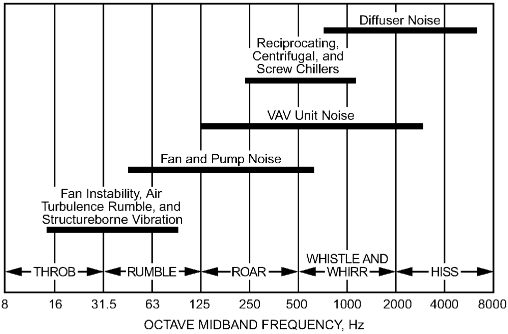


Figure 17.7 Frequencies at Which Different Types of Mechanical Equipment Generally Control Sound Spectra [2015A, Ch 48, Fig 4]

Table 17.6 Sound Transmission Class (STC) and Transmission Loss Values of Typical Mechanical Equipment Room Wall, Floor, and Ceiling Types, dB [2015A, Ch 48, Tbl 40]

		Octave Midband Frequency, Hz						
Room Construction Type	**STC**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**
200 mm CMU*	50	35	35	41	44	50	57	64
200 mm CMU with 16 mm GWB* on furring strips	53	33	32	44	50	56	59	65
16 mm GWB on both sides of 92 mm metal studs	38	18	16	33	47	55	43	47
16 mm GWB on both sides of 92 mm metal studs with fiberglass insulation in cavity	49	16	23	44	58	64	52	53
2 layers of 16 mm GWB on both sides of 92 mm metal studs with fiberglass insulation in cavity	56	19	32	50	62	67	58	63
Double row of 92 mm metal studs, 25 mm apart, each with 2 layers of 16 mm GWB and fiberglass insulation in cavity	64	23	40	54	62	71	69	74
150 mm solid concrete floor/ceiling	53	40	40	40	49	58	67	76
150 mm solid concrete floor with 100 mm isolated concrete slab and fiberglass insulation in cavity	72	44	52	58	73	87	97	100
150 mm solid concrete floor with two layers of 16 mm GWB hung on spring isolators with fiberglass insulation in cavity	84	53	63	70	84	93	104	105

Note: Actual material composition (e.g., density, porosity, stiffness) affects transmission loss and STC values.

*CMU = concrete masonry unit; GWB = gypsum wallboard.

Table 17.7 Sound Sources, Transmission Paths, and Recommended Noise Reduction Methods [2015A, Ch 48, Tbl 6]

Sound Source	Path No.
Circulating fans; grilles; registers; diffusers; unitary equipment in room	1
Induction coil and fan-powered VAV mixing units	1, 2
Unitary equipment located outside of room served; remotely located air-handling equipment, such as fans, blowers, dampers, duct fittings, and air washers	2, 3
Compressors, pumps, and other reciprocating and rotating equipment (excluding air-handling equipment)	4, 5, 6
Cooling towers; air-cooled condensers	4, 5, 6, 7
Exhaust fans; window air conditioners	7, 8
Sound transmission between rooms	9, 10

No.	Transmission Paths	Noise Reduction Methods
1	Direct sound radiated from sound source to ear	Direct sound can be controlled only by selecting quiet equipment.
	Reflected sound from walls, ceiling, and floor	Reflected sound is controlled by adding sound absorption to the room and to equipment location.
2	Air- and structureborne sound radiated from casings and through walls of ducts and plenums is transmitted through walls and ceiling into room	Design duct and fittings for low turbulence; locate high-velocity ducts in noncritical areas; isolate ducts and sound plenums from structure with neoprene or spring hangers.
3	Airborne sound radiated through supply and return air ducts to diffusers in room and then to listener by Path 1	Select fans for minimum sound power; use ducts lined with sound-absorbing material; use duct silencers or sound plenums in supply and return air ducts.
4	Noise transmitted through equipment room walls and floors to adjacent rooms	Locate equipment rooms away from critical areas; use masonry blocks or concrete for equipment room walls and floor.
5	Vibration transmitted via building structure to adjacent walls and ceilings, from which it radiates as noise into room by Path 1	Mount all machines on properly designed vibration isolators; design mechanical equipment room for dynamic loads; balance rotating and reciprocating equipment.
6	Vibration transmission along pipes and duct walls	Isolate pipe and ducts from structure with neoprene or spring hangers; install flexible connectors between pipes, ducts, and vibrating machines.
7	Noise radiated to outside enters room windows	Locate equipment away from critical areas; use barriers and covers to interrupt noise paths; select quiet equipment.
8	Inside noise follows Path 1	Select quiet equipment.
9	Noise transmitted to an air diffuser in a room, into a duct, and out through an air diffuser in another room	Design and install duct attenuation to match transmission loss of wall between rooms.
10	Sound transmission through, over, and around room partition	Extend partition to ceiling slab and tightly seal all around; seal all pipe, conduit, duct, and other partition penetrations.

18. VIBRATION

$$\text{Natural frequency,} \quad f_n = \frac{1}{2\pi}\sqrt{\frac{k}{M}} \tag{18.1}$$

where k is the stiffness of vibration isolator (force per unit deflection) and M is the mass of equipment supported by the isolator.

$$f_n = \frac{3.13}{\sqrt{\delta_{st}}}\text{Hz} \tag{18.2}$$

where δ_{st} is the static deflection of the isolator in inches.

Transmissibility is the ratio of the amplitudes of the force transmitted to the building structure to the exciting force produced by the vibrating equipment. Transmissibility is inversely proportional to the square of the disturbing frequency f_d to the natural frequency f_n.

$$T = \left[\frac{1}{1-(f_d/f_n)^2}\right] \tag{18.3}$$

At $f_d = f_n$, resonance occurs. Vibration isolation is effective only at a f_d/f_n ratio > 3.5.

When supporting structure stiffness is not large with respect to stiffness of isolator, it becomes a two-degree of freedom system. In this case, choose an isolator that will provide static deflection eight to ten times that of the estimated floor static deflection due to the added weight of the equipment. Seismic snubbers must be included in or with isolators to limit equipment movement.

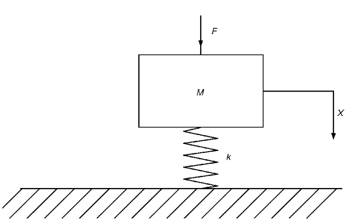


Figure 18.1 Single-Degree-of-Freedom System [2017F, Ch 8, Fig 8]

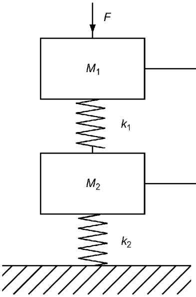


Figure 18.2 Two-Degree-of-Freedom System [2017F, Ch 8, Fig 11]

Table 18.1 Selection Guide for Vibration Isolation [2015A, Ch 48, Tbl 47]

			Equipment Location (Notes for Table 18.1, Item 1)												
						Floor Span									
			Slab on Grade			Up to 6 m			6 to 9 m			9 to 12 m			
Equipment Type	Shaft Power kW and Other	RPM	Base Type	Isolator Type	Min. Defl., mm	Base Type	Isolator Type	Min. Defl., mm	Base Type	Isolator Type	Min. Defl., mm	Base Type	Isolator Type	Min. Defl., mm	Reference Notes
Refrigeration Machines and Chillers															
Water-cooled reciprocating	All	All	A	2	6.4	A	4	19	A	4	38	A	4	64	2,3,12
Water-cooled centrifugal, scroll	All	All	A	1	6.4	A	4	19	A	4	38	A	4	38	2,3,4,8,12
Water-cooled screw	All	All	A	4	25	A	4	38	A	4	64	A	4	64	2,3,4,12
Absorption	All	All	A	1	6.4	A	4	19	A	4	38	A	4	38	
Air-cooled recip., scroll	All	All	A	1	6.4	A	4	38	A	4	38	A	4	64	2,4,5,12
Air-cooled screw	All	All	A	4	25	A	4	38	B	4	64	B	4	64	2,4,5,8,12
Air Compressors and Vacuum Pumps															
Tank-mounted horiz.	≤7.5	All	A	3	19	A	3	19	A	3	38	A	3	38	3,15
	≥7.5	All	C	3	19	C	3	19	C	3	38	C	3	38	3,15
Tank-mounted vert.	All	All	C	3	19	C	3	19	C	3	38	C	3	38	3,15
Base-mounted	All	All	C	3	19	C	3	19	C	3	38	C	3	38	3,14,15
Large reciprocating	All	All	C	3	19	C	3	19	C	3	38	C	3	38	3,14,15
Pumps															
Close-coupled	≤5.6	All	B	2	6.4	C	3	19	C	3	19	C	3	19	16
	≥5.6	All	C	3	19	C	3	19	C	3	38	C	3	38	16
Large inline	3.7 to 19	All	A	3	19	A	3	38	A	3	38	A	3	38	
	≥19	All	A	3	38	A	3	38	A	3	38	A	3	64	
	≤30	All	C	3	19	C	3	19	C	3	38	C	3	38	16
End suction and split case	30 to 93	All	C	3	19	C	3	19	C	3	38	C	3	64	10,16
	≥93	All	C	3	19	C	3	38	C	3	64	C	3	89	10,16
Packaged pump systems	All	All	A	3	19	A	3	19	A	3	38	C	3	64	

Table 18.1 Selection Guide for Vibration Isolation [2015A, Ch 48, Tbl 47] ***(Continued)***

			Equipment Location (Notes for Table 18.1, Item 1)												
						Floor Span									
	Shaft		Slab on Grade			Up to 6 m			6 to 9 m			9 to 12 m			
Equipment Type	Power kW and Other	RPM	Base Type	Isolator Type	Min. Defl., mm	Base Type	Isolator Type	Min. Defl., mm	Base Type	Isolator Type	Min. Defl., mm	Base Type	Isolator Type	Min. Defl., mm	Reference Notes
Cooling Towers		Up to 300	A	1	6.4	A	4	89	A	4	89	A	4	89	5,8,18
	All	301 to 500	A	1	6.4	A	4	64	A	4	64	A	4	64	5,18
		501 and up	A	1	6.4	A	4	19	A	4	19	A	4	38	5,18
Boilers															
Fire-tube	All	All	A	1	6.4	B	4	19	B	4	38	B	4	64	4
Water-tube, copper fin	All	All	A	1	3	A	1	3	A	1	3	B	4	6.4	
Axial Fans, Plenum Fans, Cabinet Fans, Fan Sections, Centrifugal Inline Fans															
Up to 560 mm diameter	All	All	A	2	6.4	A	3	19	A	3	19	C	3	19	4,9
610 mm diameter and up	≤500 Pa SP	Up to 300	B	3	64	C	3	89	C	3	89	C	3	89	9,8
		300 to 500	B	3	19	B	3	38	C	3	64	C	3	64	9,8
		501 and up	B	3	19	B	3	38	B	3	38	B	3	38	9,8
	≥501 Pa SP	Up to 300	C	3	64	C	3	89	C	3	89	C	3	89	3,8,9
		300 to 500	C	3	38	C	3	38	C	3	64	C	3	64	3,8,9
		501 and up	C	3	19	C	3	38	C	3	38	C	3	64	3,8,9
Centrifugal Fans															
Up to 560 mm diameter	All	All	B	2	6.4	B	3	19	B	3	19	B	3	38	9,19
610 mm diameter and up		Up to 300	B	3	64	B	3	89	B	3	89	B	3	89	8,19
	≤30	300 to 500	B	3	38	B	3	38	B	3	64	B	3	64	8,19
		501 and up	B	3	19	B	3	19	B	3	19	B	3	38	8,19
	≥37	Up to 300	C	3	64	C	3	89	C	3	89	C	3	89	2,3,8,9,19
		300 to 500	C	3	38	C	3	38	C	3	64	C	3	64	2,3,8,9,19
		501 and up	C	3	25.4	C	3	38	C	3	38	C	3	64	2,3,8,9,19
Propeller Fans															
Wall-mounted	All	All	A	1	6.4	A	1	6.4	A	1	6.4	A	1	6.4	
Roof-mounted	All	All	A	1	6.4	A	1	6.4	B	4	38	D	4	38	

Table 18.1 Selection Guide for Vibration Isolation [2015A, Ch 48, Tbl 47] ***(Continued)***

			Equipment Location (Notes for Table 18.1, Item 1)												
						Floor Span									
			Slab on Grade			Up to 6 m			6 to 9 m			9 to 12 m			
Equipment Type	Shaft Power kW and Other	RPM	Base Type	Isolator Type	Min. Defl., mm	Base Type	Isolator Type	Min. Defl., mm	Base Type	Isolator Type	Min. Defl., mm	Base Type	Isolator Type	Min. Defl., mm	Reference Notes
Heat Pumps, Fan-Coils, Computer Room Units	All	All	A	3	19	A	3	19	A	3	19	A/D	3	38	
Condensing Units	All	All	A	1	6.4	A	4	19	A	4	38	A/D	4	38	
Packaged AH, AC, H and V Units															
All	7.5	All	A	3	19	A	3	19	A	3	19	A	3	19	19
	7.5 to 11	Up to 300	A	3	19	A	3	89	A	3	89	C	3	89	2,4,8,19
	≤ 1kPa SP	301 to 500	A	3	19	A	3	64	A	3	64	A	3	64	4,19
		501 and up	A	3	19	A	3	38	A	3	38	A	3	38	4,19
	>11,	Up to 300	B	3	19	C	3	89	C	3	89	C	3	89	2,3,4,8,9
	> 1kPa SP	301 to 500	B	3	19	C	3	38	C	3	64	C	3	64	2,3,4,9
		501 and up	B	3	19	C	3	38	C	3	38	C	3	64	2,3,4,9
Packaged Rooftop Equipment	All	All	A/D	1	6.4	D	3	19	See Reference Note 17						5,6,8,17
Ducted Rotating Equipment															
Small fans, fan-powered boxes	≤300 L/s	All	A	3	12.7	A	3	12.7	A	3	12.7	A	3	12.7	7
	≥301 L/s	All	A	3	19	A	3	19	A	3	19	A	3	19	7
Engine-Driven Generators	All	All	A	3	19	C	3	38	C	3	64	C	3	89	2,3,4
Piping and Ducts (See sections on Isolating Vibration and Noise in Piping Systems and Isolating Duct Vibration for isolator selection.)															

Base Types:
A. No base, isolators attached directly to equipment (Note 28)
B. Structural steel rails or base (Notes 29 and 30)
C. Concrete inertia base (Note 30)
D. Curb-mounted base (Note 31)

Isolator Types:
1. Pad, rubber, or glass fiber (Notes 20 and 21)
2. Rubber floor isolator or hanger (Notes 20 and 25)
3. Spring floor isolator or hanger (Notes 22, 23, and 26)
4. Restrained spring isolator (Notes 22 and 24)
5. Thrust restraint (Note 27)
6. Air spring (Note 25)

Notes for Table: Selection Guide for Vibration Isolation

These notes are keyed to the column titled Reference Notes in 2015A, Ch 48, Tbl 47 and to other reference numbers throughout the table. Although the guide is conservative, cases may arise where vibration transmission to the building is still excessive. If the problem persists after all short circuits have been eliminated, it can almost always be corrected by altering the support path (e.g., from ceiling to floor), increasing isolator deflection, using low-frequency air springs, changing operating speed, improving rotating component balancing, or, as a last resort, changing floor frequency by stiffening or adding more mass. Assistance from a qualified vibration consultant can be very useful in resolving these problems.

Note 1. Isolator deflections shown are based on a reasonably expected floor stiffness according to floor span and class of equipment. Certain spaces may dictate higher levels of isolation. For example, bar joist roofs may require a static deflection of 38 mm over factories, but 64 mm over commercial office buildings.

Note 2. For large equipment capable of generating substantial vibratory forces and structureborne noise, increase isolator deflection, if necessary, so isolator stiffness is less than one-tenth the stiffness of the supporting structure, as defined by the deflection due to load at the equipment support.

Note 3. For noisy equipment adjoining or near noise-sensitive areas, see the section on Mechanical Equipment Room Sound Isolation.

Note 4. Certain designs cannot be installed directly on individual isolators (type A), and the equipment manufacturer or a vibration specialist should be consulted on the need for supplemental support (base type).

Note 5. Wind load conditions must be considered. Restraint can be achieved with restrained spring isolators (type 4), supplemental bracing, snubbers, or limit stops. Also see Chapter 55 of the 2015 *ASHRAE Handbook—HVAC Applications*.

Note 6. Certain types of equipment require a curb-mounted base (type D). Airborne noise must be considered.

Note 7. See section on Resilient Pipe Hangers and Supports for hanger locations adjoining equipment and in equipment rooms.

Note 8. To avoid isolator resonance problems, select isolator deflection so that resonance frequency is 40% or less of the lowest normal operating speed of equipment (see Chapter 8 in the 2013 *ASHRAE Handbook—Fundamentals*). Some equipment, such as variable-frequency drives, and high-speed equipment, such as screw chillers and vaneaxial fans, contain very-high-frequency vibration. This equipment creates new technical challenges in the isolation of high-frequency noise and vibration from a building's structure. Structural resonances both internal and external to the isolators can significantly degrade their performance at high frequencies. Unfortunately, at present no test standard exists for measuring the high-frequency dynamic properties of isolators, and commercially available products are not tested to determine their effectiveness for high frequencies. To reduce the chance of high-frequency vibration transmission, add a minimum 20 mm thick elastomeric pad (type 1, Note 20) to the base plate of spring isolators (type 3, Note 22, 23, 24). For some sensitive locations, air springs (Note 25) may be required. If equipment is located near extremely noise-sensitive areas, follow the recommendations of an acoustical consultant.

Note 9. To limit undesirable movement, thrust restraints (type 5) are required for all ceiling-suspended and floor-mounted units operating at 500 Pa or more total static pressure.

Note 10. Pumps over 55 kW may need extra mass and restraints.

Note 11. See text for full discussion.

Isolation for Specific Equipment

Note 12. Refrigeration Machines: Large centrifugal, screw, and reciprocating refrigeration machines may generate very high noise levels; special attention is required when such equipment is installed in upper-story locations or near noise-sensitive areas. If equipment is located near extremely noise-sensitive areas, follow the recommendations of an acoustical consultant.

Note 13. Compressors: The two basic reciprocating compressors are (1) single- and double-cylinder vertical, horizontal or L-head, which are usually air compressors; and (2) Y, W, and multihead or multicylinder air and refrigeration compressors. Single- and double-cylinder compressors generate high vibratory forces requiring large inertia bases (type C) and are generally not suitable for upper-story locations. If this equipment must be installed in an upper-story location or at-grade location near noise-sensitive areas, the expected maximum unbalanced force data must be obtained from the equipment manufacturer and a vibration specialist consulted for design of the isolation system.

Note 14. Compressors: When using Y, W, and multihead and multicylinder compressors, obtain the magnitude of unbalanced forces from the equipment manufacturer so the need for an inertia base can be evaluated.

Note 15. Compressors: Base-mounted compressors through 4 kW and horizontal tank-type air compressors through 8 kW can be installed directly on spring isolators (type 3) with structural bases (type B) if required, and compressors 10 to 75 kW on spring isolators (type 3) with inertia bases (type C) with a mass 1 to 2 times the compressor mass.

Note 16. Pumps: Concrete inertia bases (type C) are preferred for all flexible-coupled pumps and are desirable for most close-coupled pumps, although steel bases (type B) can be used. Close-coupled pumps should not be installed directly on individual isolators (type A) because the impeller usually overhangs the motor support base, causing the rear mounting to be in tension. The primary requirements for type C bases are strength and shape to accommodate base elbow supports. Mass is not usually a factor, except for pumps over 55 kW, where extra mass helps limit excess movement due to starting torque and forces. Concrete bases (type C) should be designed for a thickness of one-tenth the longest dimension with minimum thickness as follows: (1) for up to 20 kW, 150 mm; (2) for 30 to 55 kW, 200 mm; and (3) for 75 kW and up, 300 mm.

Pumps over 55 kW and multistage pumps may exhibit excessive motion at start-up (“heaving”); supplemental restraining devices can be installed if necessary. Pumps over 90 kW may generate high starting forces; consult a vibration specialist.

Note 17. Packaged Rooftop Air-Conditioning Equipment: This equipment is usually installed on low-mass structures that are susceptible to sound and vibration transmission problems. The noise problems are compounded further by curb-mounted equipment, which requires large roof openings for supply and return air.

The table shows type D vibration isolator selections for all spans up to 6 m, but extreme care must be taken for equipment located on spans of over 6 m, especially if construction is open web joists or thin, low-mass slabs. The recommended procedure is to determine the additional deflection caused by equipment in the roof. If additional roof deflection is 6 mm or less, the isolator should be selected for up to 10 times the additional roof deflection. If additional roof deflection is over 6 mm, supplemental roof stiffening should be installed to bring the roof deflection down below 6 mm, or the unit should be relocated to a stiffer roof position.

For mechanical units capable of generating high noise levels, mount the unit on a platform above the roof deck to provide an air gap (buffer zone) and locate the unit away from the associated roof penetration to allow acoustical treatment of ducts before they enter the building.

Some rooftop equipment has compressors, fans, and other equipment isolated internally. This isolation is not always reliable because of internal short-circuiting, inadequate static deflection, or panel resonances. It is recommended that rooftop equipment over 135 kg be isolated externally, as if internal isolation was not used.

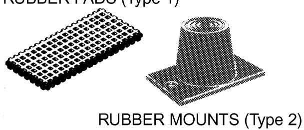
Note 18. Cooling Towers: These are normally isolated with restrained spring isolators (type 4) directly under the tower or tower dunnage. High-deflection isolators proposed for use directly under the motor-fan assembly must be used with extreme caution to ensure stability and safety under all weather conditions. See Note 5.

Note 19. Fans and Air-Handling Equipment: Consider the following in selecting isolation systems for fans and air-handling equipment:

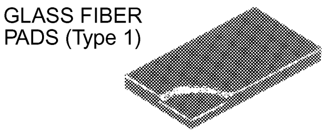
1. Fans with wheel diameters of 560 mm and less and all fans operating at speeds up to 300 rpm do not generate large vibratory forces. For fans operating under 300 rpm, select isolator deflection so the isolator natural frequency is 40% or less than the fan speed. For example, for a fan operating at 275 rpm, 0.4 ´ 275 = 110 rpm. Therefore, an isolator natural frequency of 110 rpm or lower is required. This can be accomplished with a 75 mm deflection isolator (type 3).
2. Flexible duct connectors should be installed at the intake and discharge of all fans and air-handling equipment to reduce vibration transmission to air duct structures.
3. Inertia bases (type C) are recommended for all class 2 and 3 fans and air-handling equipment because extra mass allows the use of stiffer springs, which limit heaving movements.
4. Thrust restraints (type 5) that incorporate the same deflection as isolators should be used for all fan heads, all suspended fans, and all base-mounted and suspended air-handling equipment operating at 500 Pa or more total static pressure. Restraint movement adjustment must be made under normal operational static pressures.

Vibration Isolators: Materials, Types, and Configurations

Notes 20 through 32 include figures to assist in evaluating commercially available isolators for HVAC equipment. The isolator selected for a particular application depends on the required deflection, life, cost, and compatibility with associated structures.

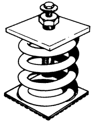


Note 20. Rubber isolators are available in pad (type 1) and molded (type 2) configurations. Pads are used in single or multiple layers. Molded isolators come in a range of 30 to 70 durometer (a measure of stiffness). Material in excess of 70 durometer is usually ineffective because durometers are not a measure of stiffness of an isolator. Isolators are designed for up to 13 mm deflection, but are used where 8 mm or less deflection is required. Solid rubber and composite fabric and rubber pads are also available. They provide high load capacities with small deflection and are used as noise barriers under columns and for pipe supports. These pad types work well only when they are properly loaded and the mass load is evenly distributed over the entire pad surface. Metal loading plates can be used for this purpose.



Note 21. Glass fiber with elastic coating (type 1). This type of isolation pad is precompressed molded fiberglass pads individually coated with a flexible, moisture-impervious elastomeric membrane. Natural frequency of fiberglass vibration isolators should be essentially constant for the operating load range of the supported equipment. Mass load is evenly distributed over the entire pad surface. Metal loading plates can be used for this purpose.

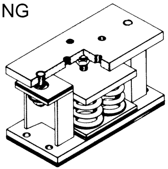
SPRING ISOLATOR (Type 3)



Note 22. Steel springs are the most popular and versatile isolators for HVAC applications because they are available for almost any deflection and have a virtually unlimited life. Spring isolators may have a rubber acoustical barrier to reduce transmission of high-frequency vibration and noise that can migrate down the steel spring coil. They should be corrosion protected if installed outdoors or in a corrosive environment. The basic types include the following:

Note 23. *Open spring isolators* (type 3) consist of top and bottom load plates with adjustment bolts for leveling equipment. Springs should be designed with a horizontal stiffness of at least 80% of the vertical stiffness (k_x/k_y) to ensure stability. Similarly, the springs should have a minimum ratio of 0.8 for the diameter divided by the deflected spring height.

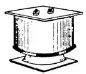
RESTRAINED SPRING ISOLATOR (Type 4)



Note 24. *Restrained spring isolators* (type 4) have hold-down bolts to limit vertical as well as horizontal movement. They are used with (a) equipment with large variations in mass (e.g., boilers, chillers, cooling towers) to restrict movement and prevent strain on piping when water is removed, (b) outdoor equipment, such as condensing units and cooling towers, to prevent excessive movement due to wind loads, and (c) with any equipment subject to seismic forces. Spring criteria should be the same as open spring isolators, and snubbers should have adequate clearance so that they are activated only when a temporary restraint is needed. See Chapter 55 of the 2015 *ASHRAE Handbook—HVAC Applications* for typical snubber types.

Closed mounts or *housed spring isolators* consist of two telescoping housings separated by a resilient material. These provide lateral snubbing and some vertical damping of equipment movement, but do not limit the vertical movement. Additional vertical snubbers must be used where vertical travel must be limited (see Chapter 55 of the 2015 *ASHRAE Handbook—HVAC Applications*). Care should be taken in selection and installation to minimize binding and short circuiting.

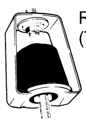
AIR SPRINGS (Type 6)

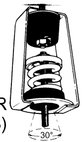


ROLLING LOBE

BELLOWS

Note 25. Air springs (type 6) can be designed for any frequency, but are economical only in applications with natural frequencies of 1.33 Hz or less (150 mm or greater deflection). They do not transmit high-frequency noise and are often used to replace high-deflection springs on problem jobs (e.g., large transformers on upper-floor installations). A constant air supply (an air compressor with an air dryer) and leveling valves are typically required.


RUBBER HANGER
(Type 2)

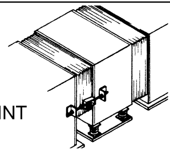


SPRING HANGER
(Type 3)

Note 26. Isolation hangers (types 2 and 3) are used for suspended pipe and equipment and have rubber, springs, or a combination of spring and rubber elements. Criteria should be similar to open spring isolators, though lateral stability is less important. Where support rod angular misalignment is a concern, use hangers that have sufficient clearance and/or incorporate rubber bushings to prevent the rod from touching the housing. Swivel or traveler arrangements may be necessary for connections to piping systems subject to large thermal movements.

Precompressed spring hangers incorporate some means of precompression or preloading of the isolator spring to minimize movement of the isolated equipment or system. These are typically used on piping systems that can change mass substantially between installation and operation.

THRUST RESTRAINT
(Type 5)

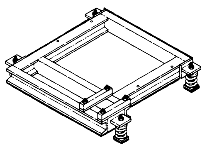


Note 27. Thrust restraints (type 5) are similar to spring hangers or isolators and are installed in pairs to resist the thrust caused by air pressure. These are typically sized to limit lateral movement to 6.4 mm or less.

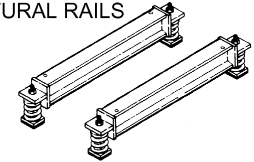
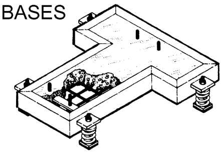
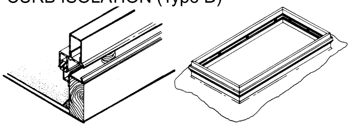
DIRECT ISOLATION (Type A)

Note 28. Direct isolation (type A) is used when equipment is unitary and rigid and does not require additional support. Direct isolation can be used with large chillers, some fans, packaged air-handling units, and air-cooled condensers. If there is any doubt that the equipment can be supported directly on isolators, use structural bases (type B) or inertia bases (type C), or consult the equipment manufacturer.

STRUCTURAL
BASES (Type B)



Note 29. Structural bases (type B) are used where equipment cannot be supported at individual locations and/or where some means is necessary to maintain alignment of component parts in equipment. These bases can be used with spring or rubber isolators (types 2 and 3) and should have enough rigidity to resist all starting and operating forces without supplemental hold-down devices. Bases are made in rectangular configurations using structural members with a depth equal to one-tenth the longest span between isolators. Typical base depth is between 100 and 300 mm, except where structural or alignment considerations dictate otherwise.

STRUCTURAL RAILS (Type B) 	**Note 30.** Structural rails (type B) are used to support equipment that does not require a unitary base or where the isolators are outside the equipment and the rails act as a cradle. Structural rails can be used with spring or rubber isolators and should be rigid enough to support the equipment without flexing. Usual practice is to use structural members with a depth one-tenth of the longest span between isolators, typically between 100 and 300 mm, except where structural considerations dictate otherwise.
CONCRETE BASES (Type C) 	**Note 31.** Concrete bases (type C) are used where the supported equipment requires a rigid support (e.g., flexible-coupled pumps) or excess heaving motion may occur with spring isolators. They consist of a steel pouring form usually with welded-in reinforcing bars, provision for equipment hold-down, and isolator brackets. Like structural bases, concrete bases should be sized to support piping elbow supports, rectangular or T-shaped, and for rigidity, have a depth equal to one-tenth the longest span between isolators. Base depth is typically between 150 and 300 mm unless additional depth is specifically required for mass, rigidity, or component alignment.
CURB ISOLATION (Type D) 	**Note 32.** Curb isolation systems (type D) are specifically designed for curb-supported rooftop equipment and have spring isolation with a watertight, and sometimes airtight, assembly. *Rooftop rails* consist of upper and lower frames separated by nonadjustable springs and rest on top of architectural roof curbs. *Isolation curbs* incorporate the roof curb into their design as well. Both kinds are designed with springs that have static deflections in the 25 to 75 mm range to meet the design criteria described in type 3. Flexible elastomeric seals are typically most effective for weatherproofing between the upper and lower frames. A continuous sponge gasket around the perimeter of the top frame is typically applied to further weatherproof the installation.

19. HVAC SYSTEMS AND EQUIPMENT

For discussion of boilers, compressors, chillers, and cooling towers, see the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*.

Furnaces

Furnaces are self-enclosed, permanently installed major appliances that provide heated air through ductwork to the space being heated. In addition, a furnace may provide the indoor fan necessary for circulating heated or cooled air from a split or single-package air conditioner or heat pump. Furnaces may be used in either residential or commercial applications, and may be grouped according to the following characteristics:

- Heat source: electricity, natural gas/propane (fan assisted, condensing or noncondensing), or oil (forced draft with power atomizing burner)
- Installation location: within conditioned space (indoors), or outside conditioned space (either outdoors, or inside the structure but not within the conditioned space)
- Combustion air source: direct vent (outdoor air) or indoor air
- Mounting arrangement and airflow: horizontal, vertical upflow, vertical downflow, or multiposition

Furnaces that use electricity as a heat source include one or more resistance-type heating elements that heats the circulating air either directly or through a metal sheath that encloses the resistance element. In gas- or oil-fired furnaces, combustion occurs in the heat exchanger sections or in a combustion chamber, with direct-spark, hot-surface, or electric ignition. Circulating air passes over the outer surfaces of a heat exchanger so that it does not contact the fuel or the products of combustion, which are passed to the outdoor atmosphere through a vent.

In North America, natural gas is the most common fuel supplied for residential heating, and the central-system forced-air furnace (Figure 19.1) is the most common way of heating with natural gas.

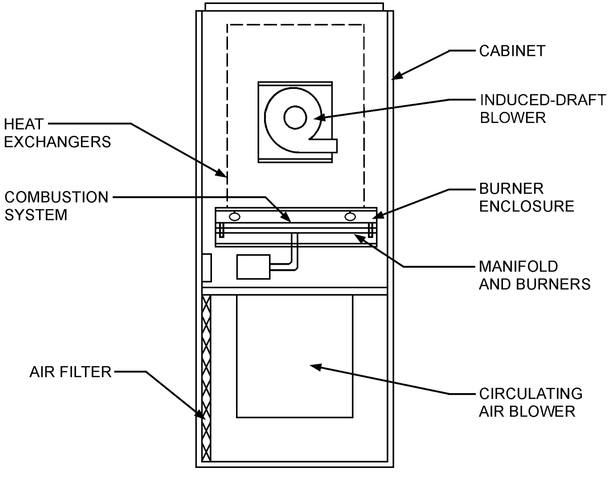


Figure 19.1 Induced-Draft Gas Furnace [2016S, Ch 33, Fig 1]

Furnaces with gas-fired burners have heat exchangers that are typically made either of left/right sets of formed parts that are joined together to form a clamshell, finless tubes bent into a compact form, or finned-tube (condensing) heat exchangers. Standard indoor furnace heat exchangers are generally made of alloy steel. Common corrosion-resistant materials include aluminized steel and stainless steel. Furnaces certified for use downstream of a cooling coil must have corrosion-resistant heat exchangers.

Heat exchangers of oil-fired furnaces are normally heavy-gage steel formed into a welded assembly. Hot flue products flow through the inside of the heat exchanger into the chimney, and conditioned air flows over the outside of the heat exchanger and into the air supply plenum.

Fan-assisted combustion furnaces use a small blower to induce flue products through the furnace. Induced-draft furnaces may or may not have a relief air opening, but they meet the same safety requirements regardless. Residential furnaces built since 1987 are equipped with a blocked-vent shutoff switch to shut down the furnace in case the vent becomes blocked.

Direct-vent furnaces use outdoor air for combustion. Outdoor air is supplied to the furnace combustion chamber by direct connections between the furnace and the outdoor air. If the vent or the combustion air supply becomes blocked, the furnace control system will shut down the furnace.

ANSI Standard Z21.47/CSA 2.3 classifies venting systems. Central furnaces are categorized by temperature and pressure attained in the vent and by the steady-state efficiency attained by the furnace. Although ANSI Standard Z21.47/CSA 2.3 uses 83% as the steady-state efficiency dividing central furnace categories, a general rule of thumb is as follows:

Category I: nonpositive vent pressure and flue loss of 17% or more
Category II: nonpositive vent pressure and flue loss less than 17%
Category III: positive vent pressure and flue loss of 17% or more
Category IV: positive vent pressure and flue loss less than 17%

Furnaces rated in accordance with ANSI Standard Z21.47/CSA 2.3 that are not direct vent are marked to show that they are in one of these four venting categories.

Ducted-system, oil-fired, forced-air furnaces are usually forced draft.

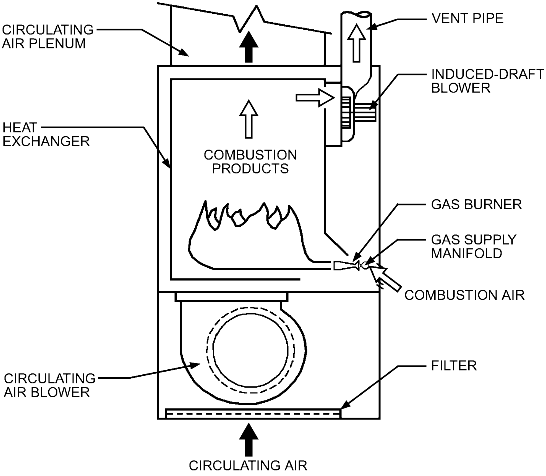


Figure 19.2 Upflow Category I Furnace with Induced-Draft Blower [2016S, Ch 33, Fig 2]

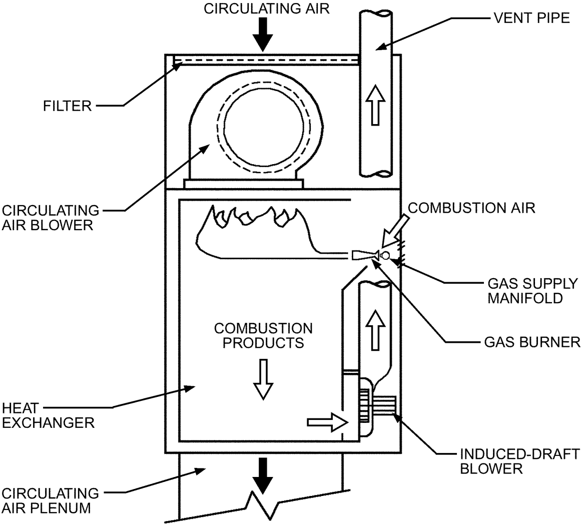


Figure 19.3 Downflow (Counterflow) Category I Furnace with Induced-Draft Blower
[2016S, Ch 33, Fig 3]

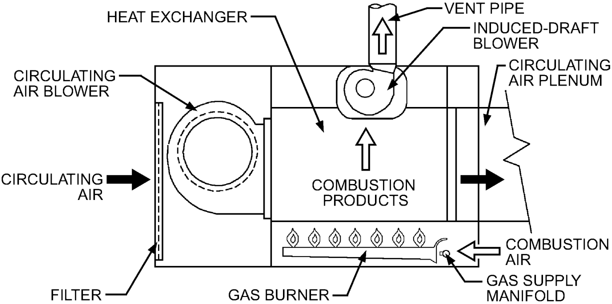


Figure 19.4 Horizontal Category I Furnace with Induced-Draft Blower
[2016S, Ch 33, Fig 4]

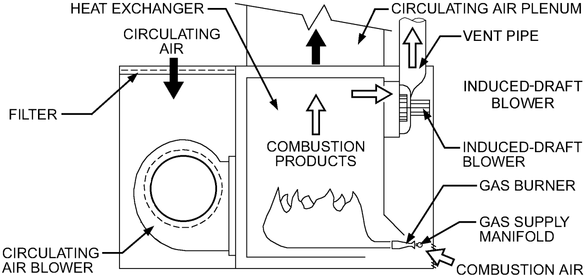


Figure 19.5 Basement (Lowboy) Category I Furnace with Induced-Draft Blower
[2016S, Ch 33, Fig 5]

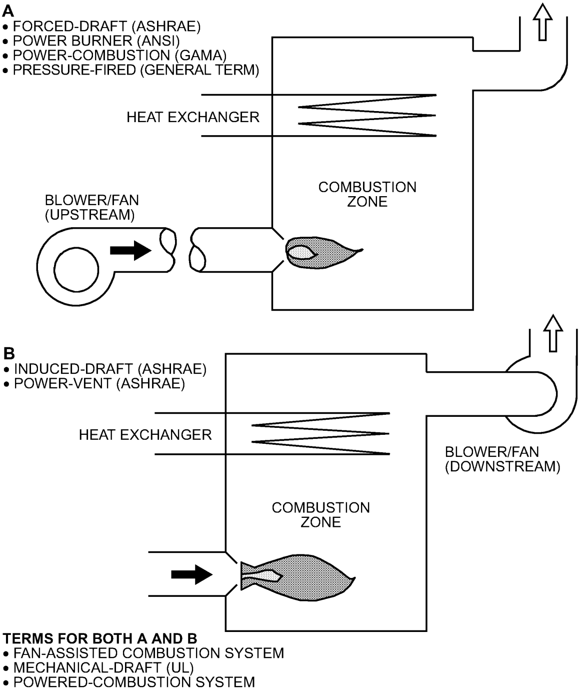


Figure 19.6 Terminology Used to Describe Fan-Assisted Combustion [2016S, Ch 33, Fig 6]

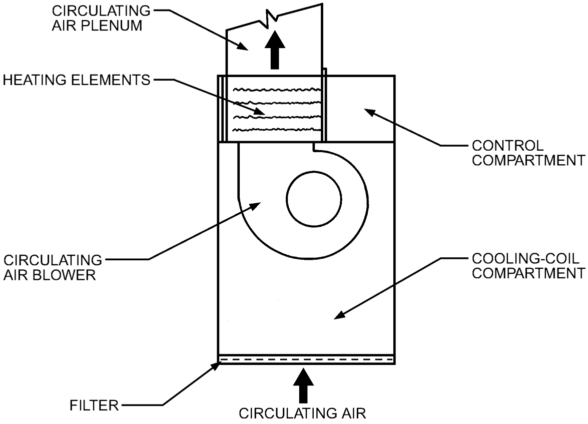


Figure 19.7 Electric Forced-Air Furnace [2016S, Ch 33, Fig 7]

Furnaces with capacities above 44 kW are classifiied as commercial furnaces. The other basic differences between residential and commercial furnaces are available options such as economizers, outdoor air dampers, and the type of electrical service required (three-phase).

Commercial heating equipment comes in almost as many flow arrangements and design variations as residential equipment. Some are identical to residential equipment, whereas others are unique to commercial applications. Some commercial units function as a part of a ducted system, and others operate as unducted space heaters.

Externally, the furnace is controlled by a low-voltage room thermostat.

Several types of gas valves perform various functions within the furnace. The type of valve available relates closely to the type of ignition device used. **Two-stage valves**, available on some furnaces, operate at full gas input or at a reduced rate, and are controlled by either a two-stage thermostat or a software algorithm programmed in the furnace control system.

The **fan control switch** controls the circulating air blower. This switch may be temperature-sensitive and exposed to the circulating airstream in the furnace cabinet, or it may be an electronically operated relay. Blower start-up is typically delayed about 1 min after burner start-up. This delay gives the heat exchangers time to warm up and reduces the flow of cold air when the blower comes on. Blower shutdown is also delayed several minutes after burner shutdown to remove residual heat from the heat exchangers and to improve the annual efficiency of the furnace.

The **limit switch** prevents overheating in the event of severe reduction in circulating airflow. This temperature-sensitive switch is exposed to the circulating airstream and shuts off the heat source (e.g., gas valve or electric element) if the temperature of air leaving the furnace is excessive. The fan control and limit switches are sometimes incorporated in the same housing and may be operated by the same thermostatic element. In the United States, the **blocked-vent shutoff switch** and **flame rollout switch** shut off the gas valve if the vent is blocked or when insufficient combustion air is present.

Furnaces using fan-assisted combustion feature a **pressure switch** to verify the flow of combustion air before opening the gas valve.

Electronic control systems are available in furnaces to provide sequencing of the inducer prepurge, ignition, circulating air blower operation, and inducer postpurge functions according to an algorithm provided by the manufacturer.

Furnaces can be installed inside or outside a building. For ideal air distribution, locate the unit in the center of the structure being heated. Furnaces are typically located in a closet, mechanical room, basement, attic, crawlspace, garage, or outdoors.

The type of fuel selected for heating is based on relative fuel cost, number of heating degree-days, and availability of utilities in the area. The most common fuel is natural gas because of its clean burning characteristics, and because of the continuous supply of this fuel through underground distribution networks to most urban settings. Propane and oil fuels are also commonly used. These fuels require on-site storage and periodic fuel deliveries. Electric heat is also continuously available through electrical power grids and is common especially where natural gas is not provided, or where the heating demand is small relative to the cooling demand.

Furnaces are clearly marked for the type of fuel to be used. In some cases, a manufacturer-approved conversion kit may be necessary to convert a furnace from one fuel type to another. If the fuel type is changed after the original installation, the conversion must be done by a qualified service person per the manufacturer's instructions and using the manufacturer's specified conversion kit. After conversion, the unit must be properly inspected by the local code authority.

All fuel-burning furnaces must be properly vented to the outdoors. Metal vents, masonry chimneys, and plastic vents are commonly used for furnaces. Manufacturers provide installation instructions for venting their furnaces, and Chapter 35 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* has a detailed discussion on venting.

Air for combustion enters the combustion zone through louvers or pipes. Outdoor air usually has lower levels of pollutants than are typically found in air from indoors, garages, utility rooms, and basements.

The furnace's heating capacity (i.e., the maximum heating rate the furnace can provide) is provided on the appliance rating plate; it is also available through the manufacturers' product literature.

Other factors should be considered when determining furnace capacity. Thermostat setback recovery may require additional heating capacity. Increasing furnace capacity may increase space temperature swing, and thus reduce comfort. Two-stage or step-modulating equipment could help by using the unit's maximum capacity to meet the setback recovery needs, and providing a lower stage of heating capacity at other times.

Fuel-burning furnaces are typically subdivided into two primary categories:

- **Condensing** furnaces typically have high efficiencies, ranging from 89 to 98%, because they have a specially designed secondary heat exchanger that extracts the heat of vaporization of water vapor in the exhaust. The dew-point temperatures of flue gases of condensing furnaces are significantly above the vent temperature, so plastic or other corrosion-resistant venting material is required. Condensing furnaces must be plumbed for condensate disposal.
- **Noncondensing** furnaces have generally less than 82% steady-state efficiency. This type of furnace has higher flue gas temperatures and requires either metal, masonry, or a combination of the two for venting materials.

Hydronic Heating Units and Radiators

Radiators, convectors, and baseboard and finned-tube units are heat-distributing devices used in hot-water and steam heating systems. They supply heat by a **combination of radiation and convection** and maintain the desired air temperature and/or mean radiant temperature in a space without fans. Figure 19.8 shows sections of typical heat-distributing units. In heating systems, radiant panels are also used. Units are inherently self-adjusting in the sense that heat output is based on temperature differentials; cold spaces receive more heat and warmer spaces receive less heat.

The following are the most common types of radiators:

- **Sectional radiators** are fabricated from welded sheet metal sections (generally two, three, or four tubes wide), and resemble freestanding cast-iron radiators.
- **Panel radiators** consist of fabricated flat panels (generally one, two, or three deep), with or without an exposed extended fin surface attached to the rear for increased output. These radiators are most common in Europe.
- **Tubular steel radiators** consist of supply and return headers with interconnecting parallel steel tubes in a wide variety of lengths and heights. They may be specially shaped to coincide with the building structure. Some are used to heat bathroom towel racks.
- **Specialty radiators** are fabricated of welded steel or extruded aluminum and are designed for installation in ceiling grids or floor-mounting. Various unconventional shapes are available.

Pipe coils have largely been replaced by finned tubes. See Table 5 in Chapter 28 of the 1988 *ASHRAE Handbook—Equipment* for the heat emission of such pipe coils.

A **convector** is a heat-distributing unit that operates with gravity-circulated air (natural convection). It has a heating element with a large amount of secondary surface and contains two or more tubes with headers at both ends. The heating element is surrounded by an enclosure with an air inlet below and an air outlet above the heating element.

Baseboard (or baseboard radiation) units are designed for installation along the bottom of walls in place of the conventional baseboard. They may be made of cast iron, with a substantial portion of the front face directly exposed to the room, or with a finned-tube element in a sheet metal enclosure. They use gravity-circulated room air.

Baseboard heat-distributing units are divided into three types: radiant, radiant convector, and finned tube. The **radiant** unit, which is made of aluminum, has no openings for air to pass over the wall side of the unit. Most of this unit's heat output is by radiation.

- The **radiant-convector** baseboard is made of cast iron or steel. The units have air openings at the top and bottom to allow circulation of room air over the wall side of the unit, which has extended surface to provide increased heat output. A large portion of the heat emitted is transferred by convection.
- The **finned-tube** baseboard has a finned-tube heating element concealed by a long, low sheet metal enclosure or cover. A major portion of the heat is transferred to the room by convection. The output varies over a wide range, depending on the physical dimensions and the materials used. A unit with a high relative output per unit length compared to overall heat loss (which would result in a concentration of the heating element over a relatively small area) should be avoided. Optimum comfort for room occupants is obtained when units are installed along as much of the exposed wall as possible.

Finned-tube (or fin-tube) units are fabricated from metallic tubing, with metallic fins bonded to the tube. They operate with gravity-circulated room air. Finned-tube elements are available in several tube sizes, in either steel or copper (25 to 50 mm nominal steel or 22 to 35 mm nominal copper) with various fin sizes, spacings, and materials. Resistance to steam or water flow is the same as that through standard distribution piping of equal size and type.

Finned-tube elements installed in occupied spaces generally have covers or enclosures in a variety of designs. When human contact is unlikely, they are sometimes installed bare or provided with an expanded metal grille for minimum protection.

The heat output ratings of heat-distributing units are expressed in watts or in square metres equivalent direct radiation (EDR).

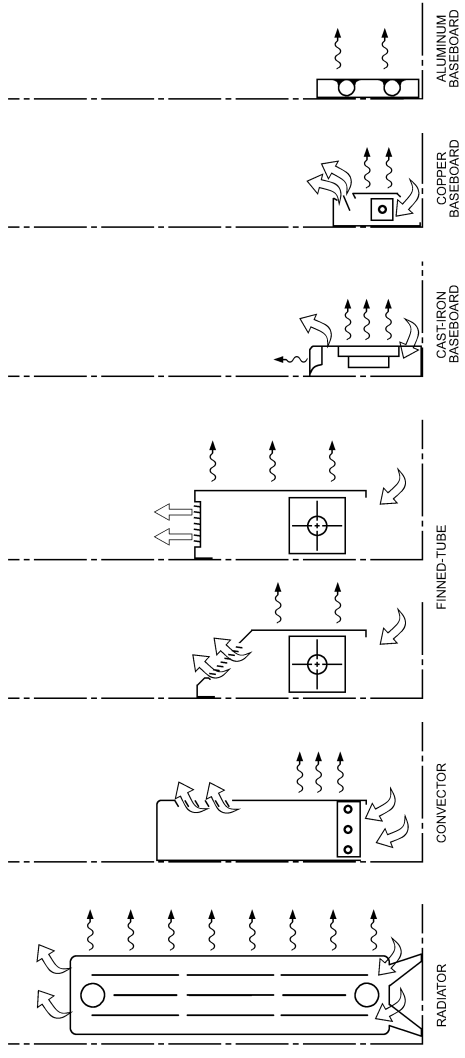


Figure 19.8 Typical Heating Units

Table 19.1 Small-Tube Cast-Iron Radiators [2016S, Ch 36, Tbl 1]

Number of Tubes per Section	Catalog Rating per Section,[a] W	Section Dimensions: A Height, mm[b]	B Width, mm Min.	B Width, mm Max.	C Spacing, mm[c]	D Leg Height, mm[b]
3	113	635	83	89	45	65
4	113	483	113	122	45	65
	127	559	113	122	45	65
	141	635	113	122	45	65
5	148	559	143	160	45	65
	169	635	143	160	45	65
6	162	483	173	203	45	65
	211	635	173	203	45	65
	260	813	173	203	45	65

[a] Ratings based on steam at 101.7°C and air at 21.1°C. They apply only to installed radiators exposed in a normal manner, not to radiators installed behind enclosures, behind grilles, or under shelves. For ratings at other temperatures, multiply table values by factors found in 2016S, Ch 36, Tbl 2.

[b] Overall height and leg height, as produced by some manufacturers, are 25 mm greater than shown in columns A and D. Radiators may be furnished without legs. Where greater than standard leg heights are required, leg height should be 115 mm.

[c] Length equals number of sections multiplied by 45 mm.

Table 19.2 Correction Factors *c* for Various Types of Heating Units [2016S, Ch 36, Tbl 2]

Steam Pressure (Approx.), kPa (absolute)	Steam or Water Temp., °C	Radiator			Convector			Finned-Tube			Baseboard		
		Room Temp., °C			Air Temp., °C			Air Temp., °C			Air Temp., °C		
		25	20	15	25	20	15	25	20	15	25	20	15
9.5	45	—	—	—	—	—	—	0.15	0.21	0.26	0.14	0.19	0.24
15.8	55	—	—	0.40	—	—	0.33	0.26	0.32	0.37	0.24	0.30	0.36
25.0	65	0.40	0.47	0.54	0.33	0.40	0.47	0.37	0.44	0.50	0.36	0.43	0.49
38.6	75	0.54	0.61	0.68	0.47	0.54	0.61	0.50	0.57	0.64	0.49	0.56	0.63
57.9	85	0.68	0.76	0.83	0.61	0.69	0.77	0.64	0.71	0.78	0.63	0.70	0.78
84.6	95	0.83	0.91	0.99	0.77	0.85	0.93	0.78	0.86	0.94	0.78	0.86	0.94
120.9	105	0.99	1.07	1.15	0.93	1.02	1.11	0.94	1.01	1.09	0.94	1.02	1.11
169.2	115	1.15	1.24	1.32	1.11	1.20	1.30	1.09	1.18	1.26	1.11	1.20	1.29
232.3	125	1.32	1.41	1.50	1.30	1.40	1.50	1.26	1.34	1.42	1.29	1.38	1.47
313.4	135	1.50	1.59	1.68	1.50	1.60	1.70	1.42	1.51	1.60	1.47	1.57	1.66
415.8	145	1.68	1.77	1.86	1.70	1.81	1.92	1.60	1.69	1.78	1.66	1.76	1.86

Note:

Use these correction factors to determine output ratings for radiators, convectors, and finned-tube and baseboard units at operating conditions other than standard. Standard conditions in the United States for a radiator are 102°C heating medium temperature and 21°C room temperature (at center of space and at 1.5 m level).

Standard conditions for convectors and finned-tube and baseboard units are 102°C heating medium temperature and 18°C inlet air temperature at 101.3 kPa atmospheric pressure. Water flow is 0.9 m/s for finned-tube units. Inlet air at 18°C for convectors and finned-tube or baseboard units represents the same room comfort conditions as 21°C room air temperature for a radiator. Standard conditions for radiant panels are 50°C heating medium temperature and 20°C for room air temperature; *c* depends on panel construction.

To determine output of a heating unit under nonstandard conditions, multiply standard heating capacity by appropriate factor for actual operating heating medium and room or inlet air temperatures.

Corrections for Nonstandard Conditions

The heating capacity of a radiator, convector, baseboard, finned-tube heat-distributing unit, or radiant panel is a power function of the temperature difference between the air in the room and the heating medium in the unit, shown as

$$q = c(t_s - t_a)^n \tag{19.1}$$

where

q = heating capacity, W

c = constant determined by test

t_s = average temperature of heating medium, °C. For hot water, the arithmetic average of the entering and leaving water temperatures is used.

t_a = room air temperature, °C. Air temperature 1.5 m above the floor is generally used for radiators, whereas entering air temperature is used for convectors, baseboard units, and finned-tube units.

n = exponent that equals 1.2 for cast-iron radiators, 1.31 for baseboard radiation, 1.42 for convectors, 1.0 for ceiling heating and floor cooling panels, and 1.1 for floor heating and ceiling cooling panels. For finned-tube units, n varies with air and heating medium temperatures. Correction factors to convert heating capacities at standard rating conditions to heating capacities at other conditions are given in Table 19.2.

Equation 19.1 may also be used to calculate heating capacity at nonstandard conditions.

Designing for high temperature drops through the system (as much as 35 to 45 K in low-temperature water (LTW) systems and as much as 110 K in high-temperature systems) can result in low water velocities in the finned-tube or baseboard element. Applying very short runs designed for conventional temperature drops (i.e., 10 K) can also result in low velocities.

Figure 19.9 shows the effect of water velocity on the heat output of typical sizes of finned-tube elements. The figure is based on work done by Harris (1957) and Pierce (1963) and tests at the Hydronics Institute. The velocity correction factor F_v is

$$F_v = (V/0.9)^{0.0} \tag{19.2}$$

where V = water velocity, m/s.

Heat output varies little over the range from 0.15 to 0.9 m/s, where F_v ranges from 0.93 to 1.00. The factor drops rapidly below 0.15 m/s because flow changes from turbulent to laminar at around 0.03 m/s. Avoid such a low velocity because the output is difficult to predict accurately when designing a system. In addition, the curve is so steep in this region that small changes in actual flow have a significant effect on output. Not only does the heat transfer rate change, but the temperature drop and, therefore, the average water temperature change (assuming a constant inlet temperature).

The designer should check water velocity throughout the system and select finned-tube or baseboard elements on the basis of velocity as well as average temperature. Manufacturers of finned-tube and baseboard elements offer a variety of tube sizes, ranging from 15 mm copper tubes for small baseboard elements to 50 mm for large finned-tube units, to aid in maintenance of turbulent flow conditions over a wide range of flow.

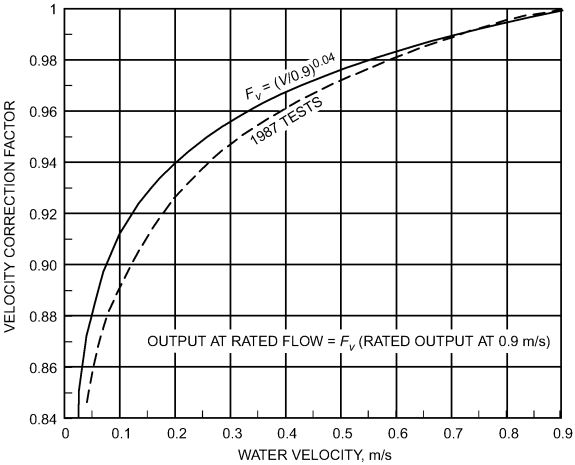


Figure 19.9 Water Velocity Correction Factor for Baseboard and Finned-Tube Radiators[2016S, Ch 36, Fig 3]

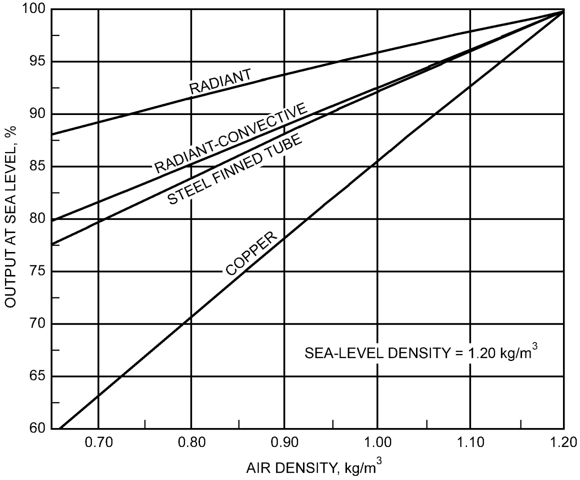


Figure 19.10 Effect of Air Density on Radiator Output [2016S, Ch 36, Fig 4]

Evaporative Cooling

Unit Ventilators, Unit Heaters, and Makeup Air Units

A heating unit ventilator is an assembly whose principal functions are to heat, ventilate, and cool a space by introducing outdoor air in quantities up to 100% of its rated capacity. The heating medium may be steam, hot water, gas, or electricity. The essential components of a heating unit ventilator are the fan, motor, heating element, damper, filter, automatic controls, and outlet grille, all of which are encased in a housing.

An **air-conditioning unit ventilator** is similar to a heating unit ventilator; however, in addition to the normal winter function of heating, ventilating, and cooling with outdoor air, it is also equipped to cool and dehumidify during the summer. It is usually arranged and controlled to introduce a fixed quantity of outdoor air for ventilation during cooling in mild weather. The air-conditioning unit ventilator may be provided with a various of combinations of heating and air-conditioning elements. Some of the more common arrangements include

- Combination hot- and chilled-water coil (two-pipe)
- Separate hot- and chilled-water coils (four-pipe)
- Hot-water or steam coil and direct-expansion coil
- Electric heating coil and chilled-water or direct-expansion coil
- Gas-fired furnace with direct-expansion coil

The typical unit ventilator has controls that allow heating, ventilating, and cooling to be varied while the fans operate continuously. In normal operation, the discharge air temperature from a unit is varied in accordance with the room requirements. The heating unit ventilator can provide **ventilation cooling** by bringing in outdoor air whenever the room temperature is above the room set point. Air-conditioning unit ventilators can provide refrigerated cooling when the outdoor air temperature is too high to be used effectively for ventilation cooling.

Unit ventilators are available for floor mounting, ceiling mounting, and recessed applications. They are available with various airflow and capacity ratings, and the fan can be arranged so that air is either blown through or drawn through the unit. With direct-expansion refrigerant cooling, the condensing unit can either be furnished as an integral part of the unit ventilator assembly or be remotely located.

Unit ventilators are used primarily in schools, meeting rooms, offices, and other areas where the density of occupancy requires controlled ventilation to meet local codes.

Floor-model unit ventilators are normally installed on an outer wall near the centerline of the room. Ceiling models are mounted against either the outer wall or one of the inside walls. Ceiling models discharge air horizontally. Best results are obtained if the unit can be placed so that the airflow is not interrupted by ceiling beams or surface-mounted lighting fixtures.

Example. A room has a heat loss of 7.0 kW at a winter outdoor design condition of –18°C and an indoor design of 21°C, with 20% outdoor air. Minimum air discharge temperature from the unit is 15°C. To obtain the specified number of air changes, a 600 L/s unit ventilator is required. Determine the ventilation heat requirement, the total heating requirement, and the ventilation cooling capacity of this unit with outdoor air temperature below 15°C.

Solution:

Ventilation heat requirement:

$$q_v = \rho c_p Q(t_i - t_o) \tag{19.3}$$

where

q_v = heat required to heat ventilating air, W
ρ = density of air at standard conditions = 1.2 kg/m^3
c_p = air specific heat = 1.0 kJ/(kg·K)
Q = ventilating airflow, L/s
t_i = required room air temperature, °C
t_o = outdoor air temperature, °C

$$q_v = 1.2 \times 1.0 \times 600 \times (20/100)[21 - (-18)] = 5600 \text{ W} \tag{19.4}$$

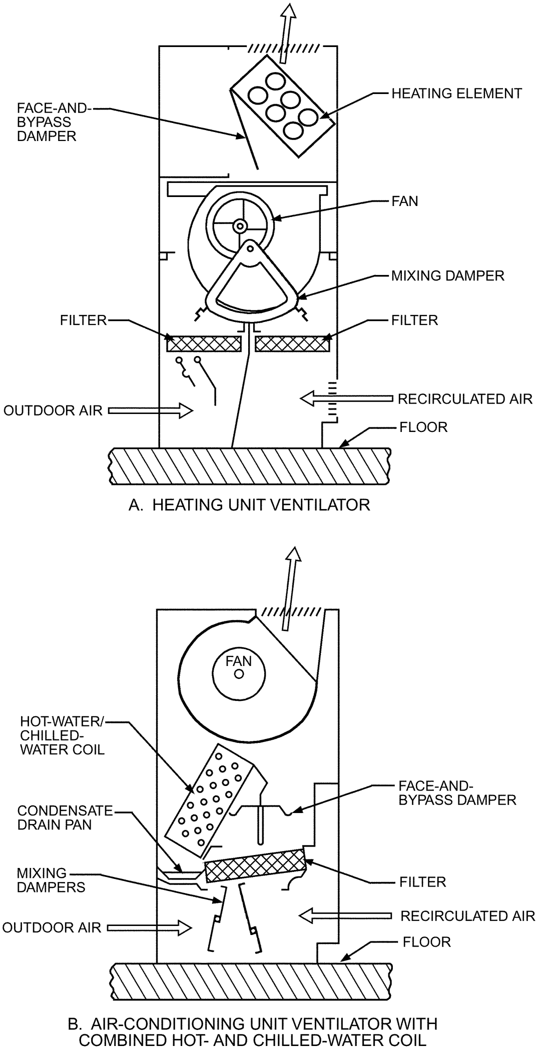
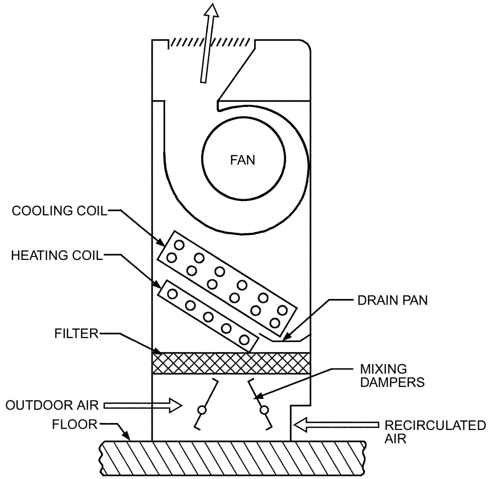
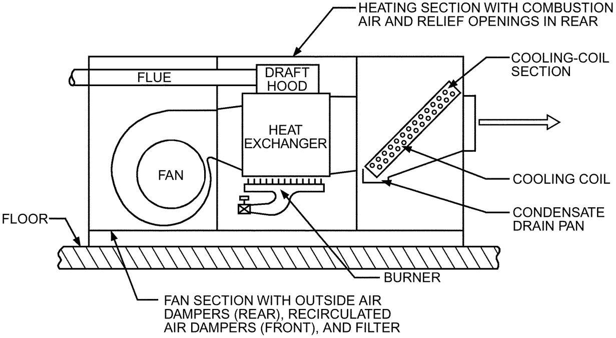


Figure 19.11 Typical Unit Ventilators [2016S, Ch 28, Fig 1]



C. AIR-CONDITIONING UNIT VENTILATOR WITH SEPARATE COILS



D. GAS-FIRED AIR-CONDITIONING UNIT VENTILATOR

Figure 19.11 Typical Unit Ventilators [2016S, Ch 28, Fig 1]
(Continued)

Table 19.3 Typical Unit Ventilator Capacities [2016S, Ch 28, Tbl 1]

Airflow, L/s	Heating Unit Ventilator Total Heating Capacity, kW	A/C Unit Ventilator Total Cooling Capacity, kW
240	10.7	5.6
360	15.6	8.4
480	20.4	11.2
600	25.3	14
720	30.2	16.8

Total heating requirement:

$$q_t = q_v + q_s \tag{19.5}$$

where

q_t = total heat requirement, W
q_s = heat required to make up heat losses, W

$$q_t = 5.6 + 7.0 = 12.6 \text{ W} \tag{19.6}$$

Ventilation cooling capacity:

$$q_c = \rho c_p Q(t_i - t_f) \tag{19.7}$$

where

q_c = ventilation cooling capacity of unit, W
t_f = unit discharge air temperature, °C

$$q_c = 1.2 \times 1.0 \times 600(21 - 15) = 4320 \text{ W} \tag{19.8}$$

Unit Heaters

A unit heater is an assembly of elements with the main function of heating a space. The essential elements are a fan and motor, a heating element, and an enclosure. Filters, dampers, directional outlets, duct collars, combustion chambers, and flues may also be included. Some types of unit heaters are shown in Figure 19.12.

Unit heaters have the following principal characteristics:

- Relatively large heating capacities in compact casings
- Ability to project heated air in a controlled manner over a considerable distance
- Relatively low installed cost per unit of heat output
- Application where an elevated sound level is permissible

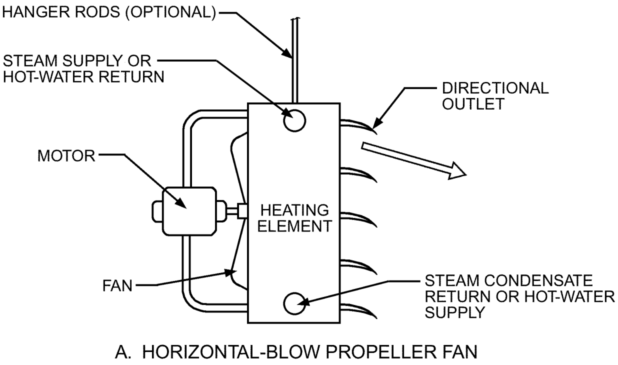
They are, therefore, usually placed in applications where the heating capacity requirements, physical volume of the heated space, or both, are too large to be handled adequately or economically by other means. By eliminating extensive duct installations, the space is freed for other use.

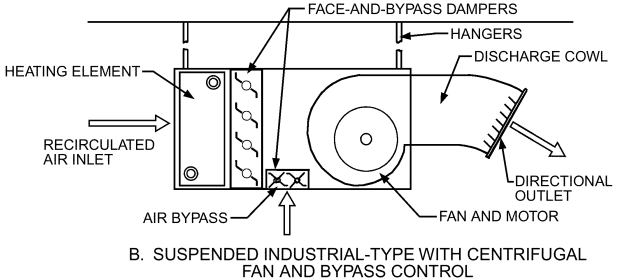
Unit heaters are mostly used for heating commercial and industrial structures such as garages, factories, warehouses, showrooms, stores, and laboratories, as well as corridors, lobbies, vestibules, and similar auxiliary spaces in all types of buildings. Unit heaters may often be used to advantage in specialized applications requiring spot or intermittent heating, such as at outer doors in industrial plants or in corridors and vestibules. Cabinet unit heaters may be used where heated air must be filtered.

The following factors should be considered when selecting a unit heater:

Heating Medium. The proper heating medium is usually determined by economics and requires examining initial cost, operating cost, and conditions of use.

Steam or **hot-water unit heaters** are relatively inexpensive but require a boiler and piping system. The unit cost of such a system generally decreases as the number of units increases. Therefore, steam or hot-water heating is most frequently used (1) in new installations involving a relatively large number of units, and (2) in existing systems that have sufficient capacity to handle the additional load. High-pressure steam or high-temperature hot-water units are normally used only in very large installations or when a high-temperature medium is required for process work. Low-pressure steam and conventional hot-water units are usually selected for smaller installations and for those concerned primarily with comfort heating.





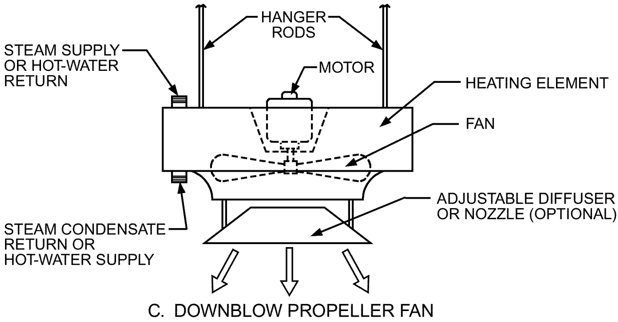
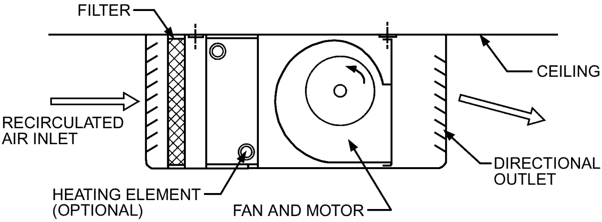
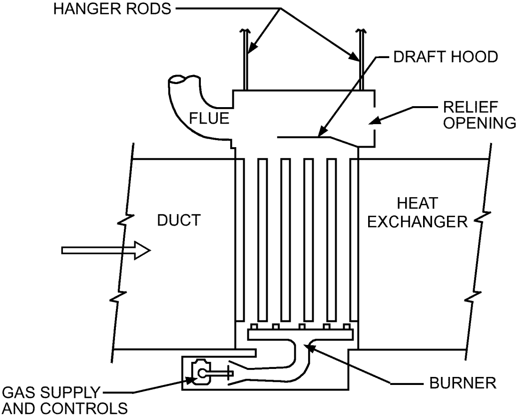


Figure 19.12 Typical Unit Heaters [2016S, Ch 28, Fig 2]

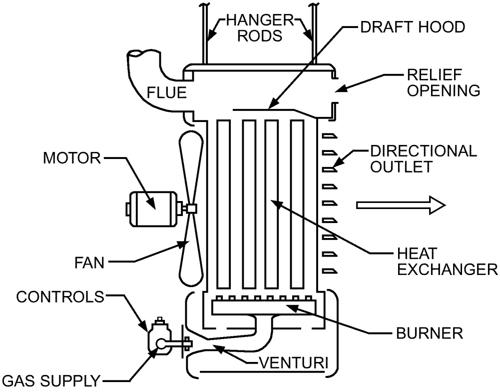


D. SUSPENDED CABINET WITH CENTRIFUGAL FAN

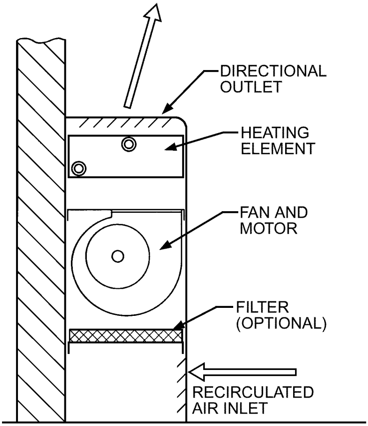


E. GAS INDIRECT-FIRED DUCT MOUNTED

Figure 19.12 Typical Unit Heaters [2016S, Ch 28, Fig 2]
(Continued)

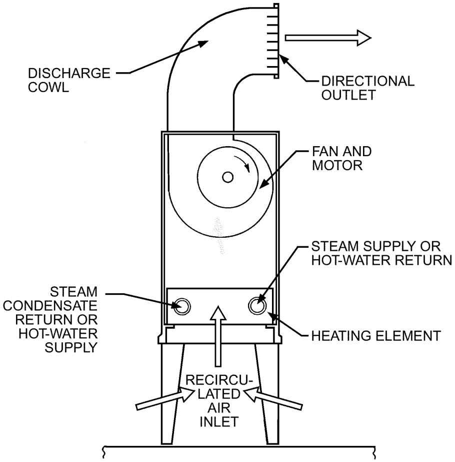


F. GAS INDIRECT-FIRED WITH PROPELLER FAN

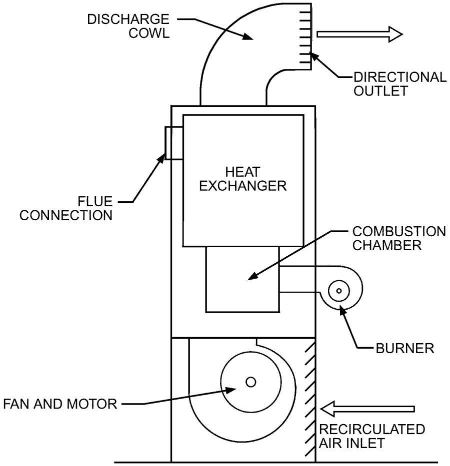


G. FLOOR-MOUNTED CABINET WITH CENTRIFUGAL FAN

Figure 19.12 Typical Unit Heaters [2016S, Ch 28, Fig 2]
(Continued)



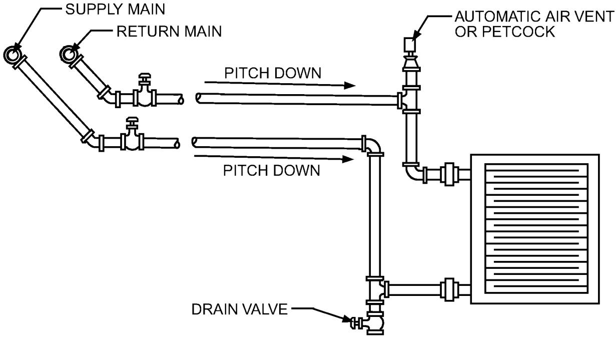
H. FLOOR-MOUNTED INDUSTRIAL-TYPE WITH CENTRIFUGAL FAN



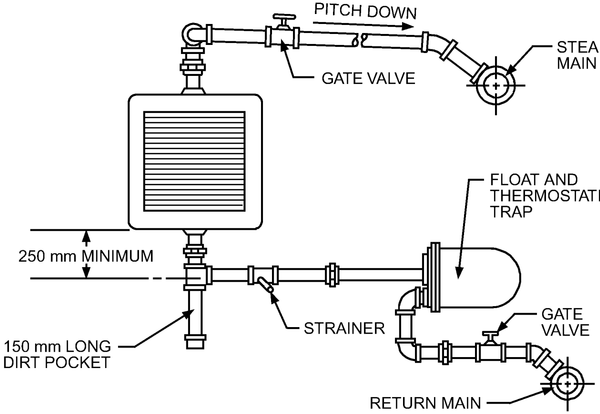
I. FLOOR-MOUNTED, INDUSTRIAL-TYPE, OIL OR GAS INDIRECT-FIRED WITH CENTRIFUGAL FAN

Figure 19.12 Typical Unit Heaters [2016S, Ch 28, Fig 2] ***(Continued)***

Evaporative Cooling

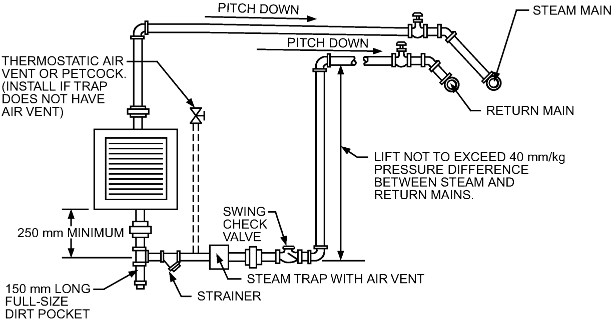


A. OVERHEAD HOT-WATER MAINS



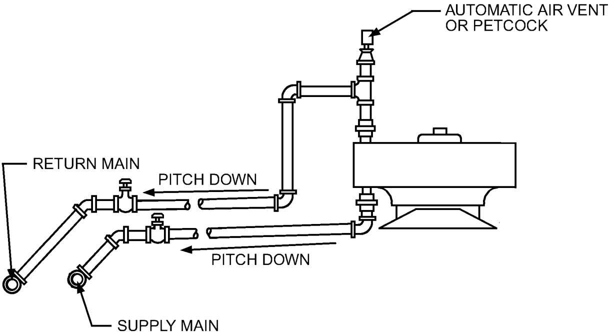
B. LOW-PRESSURE STEAM, OPEN GRAVITY, OR VACUUM RETURN

Figure 19.13 Hot Water and Steam Connections for Unit Heaters [2016S, Ch 28, Fig 4]



NOTE: This piping arrangement is only for two-position control. Modulating steam control may not provide sufficient pressure to lift condensate to return main in throttled position.

C. OVERHEAD STEAM AND RETURN MAINS



D. LOWER HOT-WATER MAINS

Figure 19.13 Hot Water and Steam Connections for Unit Heaters [2016S, Ch 28, Fig 4]
(Continued)

Gas and **oil indirect-fired unit heaters** are frequently preferred in small installations where the number of units does not justify the expense and space requirements of a new boiler system or where individual metering of the fuel supply is required, as in a shopping center. Gas indirect-fired units usually have either horizontal propeller fans or industrial centrifugal fans. Oil indirect-fired units largely have industrial centrifugal fans. Some codes limit the use of indirect-fired unit heaters in some applications. Indirect-fired oil and gas units are of blow-through design to mitigate the possibility of combustion products entering the occupied space.

Electric unit heaters are used when the cost of available electric power is lower than that of alternative fuel sources and for isolated locations, intermittent use, supplementary heating, or temporary service. Typical applications are ticket booths, security offices, factory offices, locker rooms, and other isolated rooms scattered over large areas. Electric units are particularly useful in isolated and untended pumping stations or pits, where they may be thermostatically controlled to prevent freezing.

Type of Unit. Propeller fan units are generally used in non-ducted applications where the heating capacity and distribution requirements can best be met by units of moderate output and where heated air does not need to be filtered. Horizontal-blow units are usually installed in buildings with low to moderate ceiling heights. Downblow units are used in spaces with high ceilings and where floor and wall space limitations dictate that heating equipment be kept out of the way. Downblow units may have an adjustable diffuser to vary the discharge pattern from a high-velocity vertical jet (to achieve the maximum distance of downward throw) to a horizontal discharge of lower velocity (to prevent excessive air motion in the zone of occupancy). Revolving diffusers are also available.

Cabinet unit heaters are used when a more attractive appearance is desired. They are suitable for free-air delivery or low static pressure duct applications. They may be equipped with filters, and they can be arranged to discharge either horizontally or vertically up or down.

Industrial centrifugal fan units are applied where heating capacities and space volumes are large or where filtration of the heated air or operation against static resistance is required. Downblow or horizontal-blow units may be used, depending on the requirements.

Duct unit heaters are used where the air handler is remote from the heater. These heaters sometimes provide an economical means of adding heating to existing cooling or ventilating systems with ductwork. They require flow and temperature limit controls.

Location for Proper Heat Distribution. Units must be selected, located, and arranged to provide complete heat coverage while maintaining acceptable air motion and temperature at an acceptable sound level in the working or occupied zone. Proper application depends on size, number, and type of units; direction of airflow and type of directional outlet used; mounting height; outlet velocity and temperature; and air volumetric flow. Many of these factors are interrelated.

The mounting height may be governed by space limitations or by the presence of equipment such as display cases or machinery. The higher a downblow heater is mounted, the lower the temperature of air leaving the heater must be to force the heated air into the occupied zone. Also, the distance that air leaving the heater travels depends largely on the air temperature and initial velocity. A high discharge temperature reduces the area of effective heat coverage because of its buoyancy.

For area heating, place horizontal-blow unit heaters in exterior zones such that they blow either along the exposure or toward it at a slight angle. When possible, arrange multiple units so that the discharge airstreams support each other and create a general circulatory motion in the space. Interior zones under exposed roofs or skylights should be completely blanketed. Arrange downblow units so that the heated areas from adjacent units overlap slightly to provide complete coverage.

For spot heating of individual spaces in larger unheated areas, single unit heaters may be used, but allowance must be made for the inflow of unheated air from adjacent spaces and the consequent reduction in heat coverage. Such spaces should be isolated by partitions or enclosures, if possible.

Horizontal unit heaters should have discharge outlets located well above head level. Both horizontal and vertical units should be placed so that the heated airstream is delivered to the occupied zone at acceptable temperature and velocity. Outlet air temperature of free-air delivery unit heaters used for comfort heating should be 27 to 33 K higher than the design room temperature. When possible, locate units so that they discharge into open spaces, such as aisles, and not directly on the occupants. For further information on air distribution, see Chapter 20 of the 2013 *ASHRAE Handbook—Fundamentals*.

Manufacturers' catalogs usually include suggestions for the best arrangements of various unit heaters, recommended mounting heights, heat coverage for various outlet velocities, final temperatures, directional outlets, and sound level ratings.

Steam or Hot Water. Heating capacity must be determined at a standard condition. Variations in entering steam or water temperature, entering air temperature, and steam or water flow affect capacity. Typical standard conditions for rating steam unit heaters are dry saturated steam at 14 kPa (gage) pressure at the heater coil, air at 15.6°C (101.3 kPa barometric pressure) entering the heater, and the heater operating free of external resistance to airflow. Standard conditions for rating hot-water unit heaters are entering water at 93.3°C, water temperature drop of 11.1 K, entering air at 15.6°C and 101.3 kPa barometric pressure, and the heater operating free of external resistance to airflow.

Gas-Fired. Gas-fired unit heaters are rated in terms of both input and output, in accordance with the approval requirements of the American Gas Association.

Oil-Fired. Ratings of oil-fired unit heaters are based on heat delivered at the heater outlet.

Electric. Electric unit heaters are rated based on the energy input to the heating element.

Effect of Airflow Resistance on Capacity. Unit heaters are customarily rated at free-air delivery. Airflow and heating capacity decrease if outdoor air intakes, air filters, or ducts on the inlet or discharge are used. The manufacturer should have information on the heat output to be expected at other than free-air delivery.

Effect of Inlet Temperature. Changes in entering air temperature influence the total heating capacity in most unit heaters and the final temperature in all units. Because many unit heaters are located some distance from the occupied zone, possible differences between the temperature of the air actually entering the unit and that of air being maintained in the heated area should be considered, particularly with downblow unit heaters.

Filters. Air from propeller unit heaters cannot be filtered because the heaters are designed to operate with heater friction loss only. If dust in the building must be filtered, centrifugal fan units or cabinet units should be used.

The controls for a steam or hot water unit heater can provide either (1) on/off operation of the unit fan, or (2) continuous fan operation with modulation of heat output. For on/off operation, a room thermostat is used to start and stop the fan motor or group of fan motors. A limit thermostat, often strapped to the supply or return pipe, prevents fan operation in the event that heat is not being supplied to the unit. An auxiliary switch that energizes the fan only when power is applied to open the motorized supply valve may also be used to prevent undesirable cool air from being discharged by the unit.

Continuous fan operation eliminates both the intermittent blasts of hot air resulting from on/off operation and the stratification of temperature from floor to ceiling that often occurs during off periods. In this arrangement, a proportional room thermostat controls a valve modulating the heat supply to the coil or a bypass around the heating element. A limit thermostat or auxiliary switch stops the fan when heat is no longer available.

One type of control used with downblow unit heaters is designed to automatically return the warm air, which would normally stratify at the higher level, down to the zone of occupancy. Two thermostats and an auxiliary switch are required. The lower thermostat is placed in the zone of occupancy and is used to control a two-position supply valve to the heater. An auxiliary switch is used to stop the fan when the supply valve is closed. The higher thermostat is placed near the unit heater at the ceiling or roof level where the warm air tends to stratify. The lower thermostat automatically closes the steam valve when its setting is satisfied, but the higher thermostat overrides the auxiliary switch so that the fan continues to run until the temperature at the higher level falls below a point sufficiently high to produce a heating effect.

Indirect-fired and electric units are usually controlled by intermittent operation of the heat source under control of the room thermostat, with a separate fan switch to run the fan when heat is being supplied.

Unit heaters can be used to circulate air in summer. In such cases, the heat is shut off and the thermostat has a bypass switch, which allows the fan to run independently of the controls.

Makeup Air Units

Makeup air units are designed to condition ventilation air introduced into a space or to replace air exhausted from a building. The air exhausted may be from a process or general area exhaust, through either powered exhaust fans or gravity ventilators. The units may be used to prevent negative pressure within buildings or to reduce airborne contaminants in a space. The units may heat, cool, humidify, dehumidify, and/or filter incoming air. They may be used to replace air in the conditioned space or to supplement or accomplish all or part of the airflow needed to satisfy the heating, ventilating, or cooling airflow requirements.

Makeup air systems used for ventilation may be (1) sized to balance air exhaust volumes or (2) sized in excess of the exhaust volume to dilute contaminants. In applications where contaminant levels vary, variable-flow units should be considered so that the supply air varies for contaminant control and the exhaust volume varies to track supply volume. In critical spaces, the exhaust volume may be based on requirements to control pressure in the space.

Location. Makeup air units are defined by their location or the use of a key component. Examples are rooftop makeup air units, truss- or floor-mounted units, and sidewall units. Some manufacturers differentiate their units by heating mode, such as steam or direct gas-fired makeup air units.

Rooftop units are commonly used for large single-story industrial buildings to simplify air distribution. Access (via roof walks) is more convenient than access to equipment mounted in the truss; truss units are only accessible by installing a catwalk adjacent to the air units. Disadvantages of rooftop units are (1) they increase foot traffic on the roof, thus reducing its life and increasing the likelihood of leaks; (2) inclement weather reduces equipment accessibility; and (3) units are exposed to weather.

Makeup air units can also be placed around the perimeter of a building with air ducted through the sidewall. This approach limits future building expansion, and the effectiveness of ventilating internal spaces decreases as the building gets larger. However, access to the units is good, and minimum support is required because the units are mounted on the ground.

Heaters in makeup air systems may be direct gas-fired burners, electric resistance heating coils, indirect gas-fired heaters, steam coils, or hot-water heating coils. Air distribution systems are often required to direct heat to spaces requiring it.

Mechanical refrigeration with direct-expansion or chilled-water cooling coils, direct or indirect evaporative cooling sections, or well water coils may be used. Air distribution systems are often required to direct cooling to specific spaces that experience or create heat gain.

If direct-expansion coils are used in conjunction with direct-fired gas coils, the cooling coils' headers must be isolated from the airstream and directly vented outdoors.

High-efficiency filters (approximately MERV 16 for near-HEPA performance) are not normally used in a makeup air unit because of their relatively high cost. HVAC prefilters are generally in the MERV 6 to 13 range, depending on particulate removal needs.

Follow AMCA Standard 205-12 for fan selection. Fans should have variable-speed drives for possible energy savings or for use in variable-airflow systems.

Fans should have variable-speed drives for possible energy savings or for use in variable-airflow systems.

Controls for a makeup air unit fall into the following categories: (1) local temperature controls, (2) airflow controls, (3) plant-wide controls for proper equipment operation and efficient performance, (4) safety controls for burner gas, and (5) building smoke control systems.

Safety controls for gas-fired units include components to properly light the burner and to provide a safeguard against flame failure. The heater and all attached inlet ducting must be purged with at least four air changes before initiating an ignition sequence and before reignition after a malfunction. A flame monitor and control system must be used to automatically shut off gas to the burner upon burner ignition or flame failure. Critical malfunctions include flame failure, supply fan failure, combustion air depletion, power failure, control signal failure, excessive or inadequate inlet gas supply pressure, excess air temperature, and gas leaks in motorized valves or inlet gas supply piping.

Makeup air units should be interlocked with exhaust units to avoid overpressurization, and should include shutoff dampers with limit switches for when not in use. Damper leakage rates should be within limits set in ASHRAE Standard 90.1. These units should also be interlocked to the building's fire alarm system to shut down in the case of a fire, where required by applicable codes.

Consider using automatic safety shutoff valves on interconnecting piping systems where there are risks of overtemperature, overpressure, or gas leaks.

Small Forced-Air Heating and Cooling Systems

Forced-air systems are heating and/or cooling systems that use motor-driven blowers to distribute heated, cooled, and otherwise treated air to multiple outlets for the comfort of individuals in confined spaces. A typical residential or small commercial system includes (1) a heating and/or cooling unit, (2) supply and return ductwork (including registers and grilles), (3) accessory equipment, and (4) controls (see Figure 19.14).

Three types of forced-air heating and cooling devices are (1) furnaces, (2) air conditioners, and (3) heat pumps.

Furnaces are the basic component of most forced-air heating systems (see the section in this chapter). They are manufactured to use specific fuels such as oil, natural gas, or liquefied petroleum gas, and are augmented with an air-conditioning coil when cooling is included. The fuel used dictates installation requirements and safety considerations.

Common **air-conditioning** systems use a split configuration with an air-handling unit, such as a furnace. The air-conditioning evaporator coil (indoor unit) is installed on the discharge air side of the air handler. The compressor and condensing coil (outdoor unit) are located outside the structure, and refrigerant lines connect the outdoor and indoor units.

Self-contained air conditioners contain all necessary air-conditioning components, including circulating air blowers, and may or may not include fuel-fired heat exchangers or electric heating elements.

Heat pumps cool and heat using the refrigeration cycle. They are available in split and packaged (self-contained) configurations. Generally, air-source heat pumps require supplemental heating; therefore, electric heating elements are usually included with the heat pump as part of the forced-air system. Heat pumps offer high efficiency at mild temperatures, but may be combined with fossil-fuel furnaces to minimize heating cost. Heat pump supplemental heating also may be provided by thermostat-controlled gas heating appliances (e.g., fireplaces, freestanding stoves).

Forced-air systems may be equipped with accessories that further condition the air. They may modify humidity, remove contaminants, mix outdoor air with the recirculating air, or transfer energy in other ways. Disposable air filters on the return side of forced-air systems are so common that they are not considered accessories.

A simple thermostat controlling on/off cycling of central equipment may be all that is used or needed for temperature control. Such thermostats typically have a switch for automatic or continuous fan operation, and another to choose heating, cooling, or neither.

More complex systems may provide control features for timed variations (from simple night setback to a weekly schedule of temperatures); multiple independent zones, power stages, or fan speeds; influence of outdoor sensors; humidity; automatic switching between heating and cooling modes, etc.

The overall system design should proceed as follows:

1. Estimate heating and cooling loads, including target values for duct losses.
2. Determine preliminary ductwork location and materials of ductwork and outlets.
3. Determine heating and cooling unit location.
4. Select accessory equipment. Accessory equipment is not generally provided with initial construction; however, the system may be designed for later addition of these components.
5. Select control components.
6. Select heating/cooling equipment.
7. Determine maximum airflow (cooling or heating) for each supply and return location.
8. Determine airflow at reduced heating and cooling loads (two-speed and variable-speed fans).
9. Finalize heating/cooling equipment.
10. Finalize control system.
11. Finalize duct design and size.
12. Select supply and return grilles.
13. When the duct system is in place, measure duct leakage and compare results with target values used in step 1.

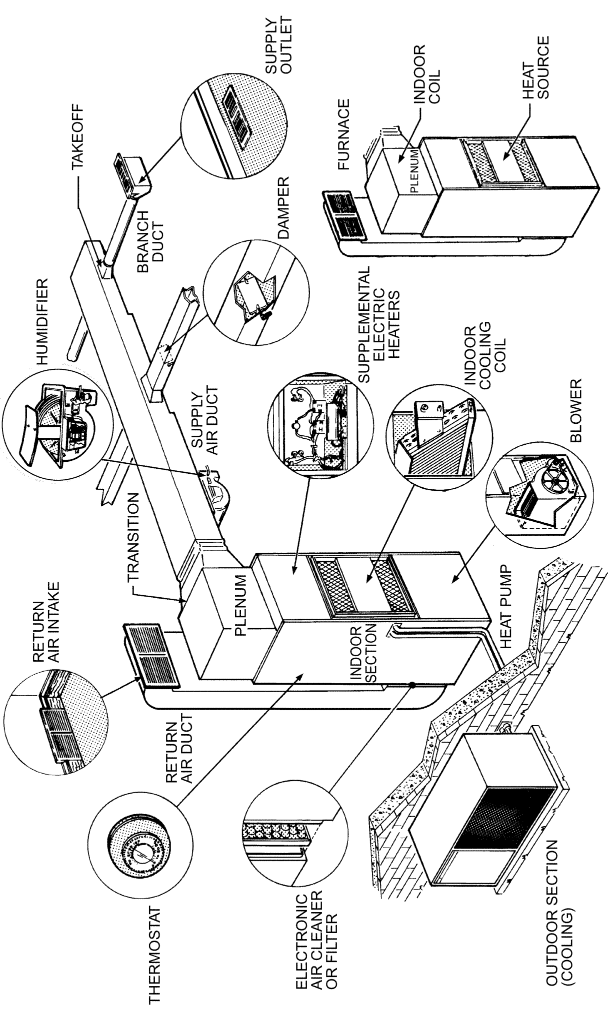


Figure 19.14 Heating and Cooling Components [2016S, Ch 10, Fig 1]

This procedure requires certain preliminary information such as location, weather conditions, and architectural considerations. See applicable sections of this guide for details on each step.

For maximum energy efficiency, ductwork and equipment should be installed in the conditioned space. The next best location is in a full basement. If a structure has an insulated, unvented, and sealed crawlspace, the ductwork and equipment can be located there (with appropriate provision for combustion air, if applicable), or the equipment can be placed in a closet or utility room. Vented attics and vented crawlspaces are the least preferred locations for ductwork and HVAC equipment.

Furnace heating output should match or slightly exceed the estimated design load. The Air Conditioning Contractors of America (ACCA *Manual* S) recommends a 40% limit on oversizing for fossil fuel furnaces. This limit minimizes venting problems associated with oversized equipment and improves part-load performance. Note that the calculated load must include duct loss, humidification load, and night setback recovery load, as well as building conduction and infiltration heat losses.

To help conserve energy, manufacturers have added features to improve furnace efficiency. Electric ignition has replaced the standing pilot; vent dampers and more efficient motors are also available. Furnaces with fan-assisted combustion systems (FACSs) and condensing furnaces also improve efficiency. Two-stage heating and cooling, variable-speed heat pumps, and two-speed and variable-speed blowers are also available.

Research on the effect of blower performance on residential forced-air heating system performance suggested reductions of 650 to 900 MJ/ yr for automatic furnace fan operation and 9360 MJ/ yr for continuous fan operation by changing from permanent split capacitor (PSC) blower motors to brushless permanent electronically commutated magnet motors (ECMs) (Phillips 1998).

A system designed to both heat and cool and that cycles cooling equipment on and off by sensing dry-bulb temperature alone should be sized to match the design heat gain as closely as possible. Oversizing under this control strategy could lead to higher-than-desired indoor humidity levels. Chapter 17 of the 2013 *ASHRAE Handbook—Fundamentals* recommends that cooling units not be oversized. Other sources suggest limiting oversizing to 15% of the sensible load. A heat pump should be sized for the cooling load with supplemental heat provided to meet heating requirements. Size air-source heat pumps in accordance with the equipment manufacturer recommendations. ACCA *Manual* S can also be used to assist in the selection and sizing of equipment.

The required airflow and the blower's static pressure limitation are the parameters around which the duct system is designed. The heat loss or gain for each space determines the proportion of the total airflow supplied to each space. Static pressure drop in supply registers should be limited to about 7.5 Pa. The required pressure drop must be deducted from the static pressure available for duct design.

The flow delivered by a single supply outlet should be determined by considering the (1) space limitations on the number of registers that can be installed, (2) pressure drop for the register at the flow rate selected, (3) adequacy of air delivery patterns for offsetting heat loss or gain, and (4) space use pattern.

Manufacturers' specifications include blower airflow for each blower speed and external static pressure combination. Determining static pressure available for duct design should include the possibility of adding accessories in the future (e.g., electronic air cleaners or humidifiers). Therefore, the highest available fan speed should not be used for design.

For systems that heat only, the blower rate may be determined from the manufacturer's data. The temperature rise of air passing through the heat exchanger of a fossil-fuel furnace must be within the manufacturer's recommended range (usually 22 to 45 K). The possible later addition of cooling should also be considered by selecting a blower that operates in the midrange of the fan speed and settings.

For cooling only, or for heating and cooling, the design flow can be estimated by Equation 19.9:

$$Q = \frac{q_s}{\rho c_p \Delta t} \tag{19.9}$$

where

Q = flow rate, L/ s
q_s = sensible load, W
ρ = air density assumed to equal 1.20 kg/ m^3
c_p = specific heat of air = 1.0 kJ/ (kg·K)
Δt = dry-bulb temperature difference between air entering and leaving equipment, K

Replacing all constant values gives the simplified equation in the given units.

$$Q = \frac{1}{1.2} \times \frac{q_s}{\Delta t} = \frac{q_s}{1.2\Delta t} \tag{19.10}$$

For preliminary design, an approximate Δt is as follows:

Sensible Heat Ratio (SHR)	**Δt, K**
0.75 to 0.79	11.5
0.80 to 0.85	10.5
0.85 to 0.90	9.5

SHR = Calculated sensible load/Calculated total load

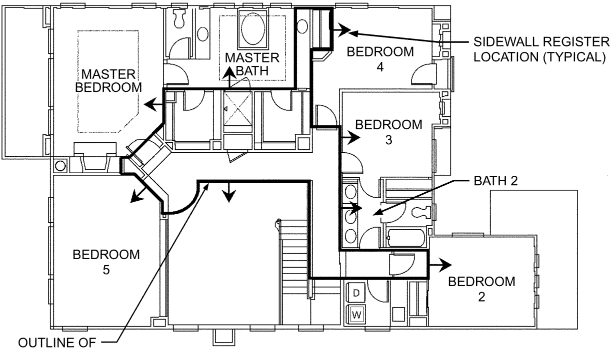
For example, if calculation indicates the sensible load is 6800 W and the latent load is 1500 W, the SHR is calculated as follows:

$$\text{SHR} = \frac{6800}{6800 + 1500} = 0.82 \tag{19.11}$$

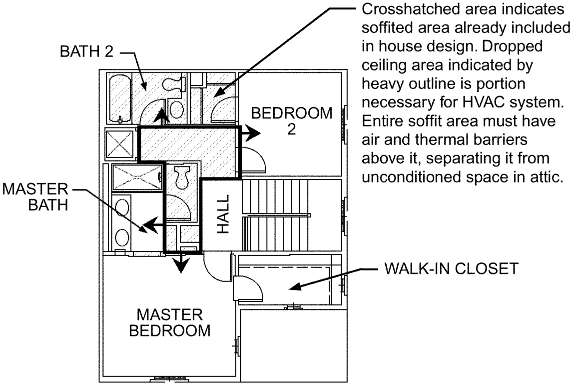
and

$$Q = \frac{6800}{1.2 + 10.5} = 540 \text{ L/s} \tag{19.12}$$

This value is the estimated design flow. The exact design flow can only be determined after the cooling unit is selected. The unit that is ultimately selected should supply an airflow in the range of the estimated flow, and must also have adequate sensible and latent cooling capacity when operating at design conditions.



(A)



(B)

Figure 19.15 Sample Floor Plans for Locating Ductwork in Second Floor of (A) Two-Story House and (B) Townhouse [2016S, Ch 10, Fig 2]
(Hedrick 2002)

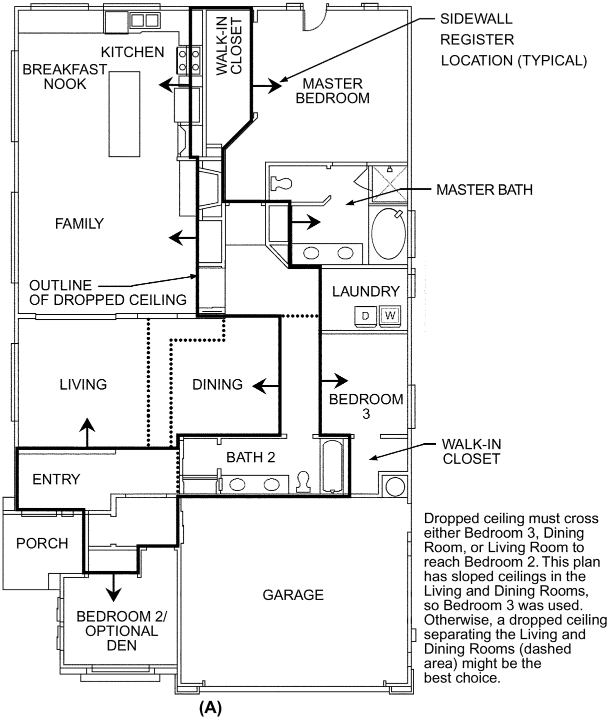
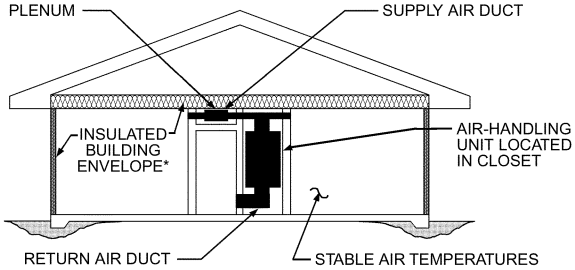
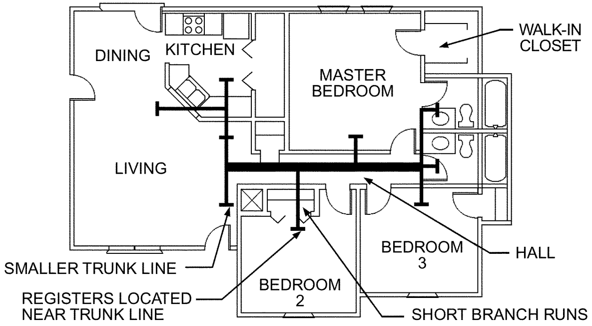


Figure 19.16 Sample Floor Plans for One-Story House with (A) Dropped Ceilings, (B) Ducts in Conditioned Spaces, and (C) Right-Sized Air Distribution in Conditioned Spaces
[2016S, Ch 10, Fig 3]
(EPA 2000)



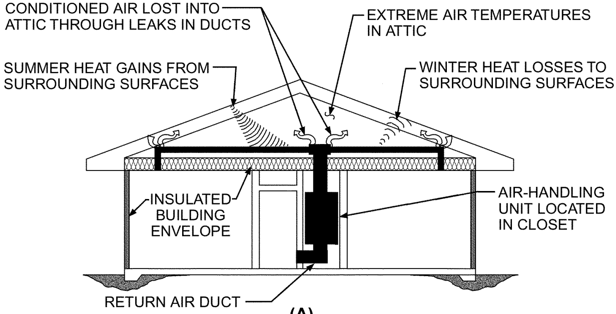
*To minimize duct leakage to attic, continuous drywall or other air barrier is needed at ceiling below insulation in all plenum areas.

(B)

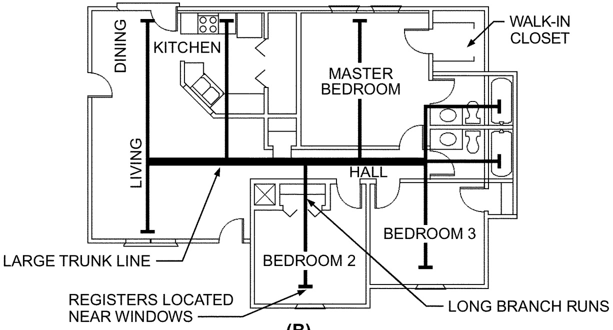


(C)

Figure 19.16 Sample Floor Plans for One-Story House with (A) Dropped Ceilings, (B) Ducts in Conditioned Spaces, and (C) Right-Sized Air Distribution in Conditioned Spaces
[2016S, Ch 10, Fig 3] ***(Continued)***
(EPA 2000)



(A)



(B)

Figure 19.17 (A) Ducts in Unconditioned Spaces and (B) Standard Air Distribution System in Unconditioned Spaces [2016S, Ch 10, Fig 4]
(EPA 2000)

Unitary Air Conditioners and Heat Pumps

Unitary air conditioners are factory-made assemblies that nor-mally include an evaporator or cooling coil and a compressor/ condenser combination, and possibly provide heating as well. An **air-source unitary heat pump** normally includes an indoor conditioning coil, compressor(s), and an outdoor coil. It must provide heating and possibly cooling as well. A **water-source heat pump** rejects or extracts heat to and from a water loop instead of from ambient air. A unitary air conditioner or heat pump with more than one factory-made assembly (e.g., indoor and outdoor units) is commonly called a **split system**.

Unitary equipment is divided into three general categories: residential, light commercial, and commercial. Residential equipment is single-phase unitary equipment with a cooling capacity of 19 kW or less and is designed specifically for residential application. Light commercial equipment is generally three-phase, with cooling capacity up to 40 kW, and is designed for small businesses and commercial properties. Commercial unitary equipment has cooling capacity higher than 40 kW and is designed for large commercial buildings.

Unitary equipment is available in many configurations, such as

- **Single-zone, constant-volume**, which consists of one controlled space with one thermostat that controls to maintain a set point. This equipment may be single stage, multistage, or variable capacity.
- **Multizone, constant-volume**, which has several controlled spaces served by one unit that supplies air of different temperatures to different zones as demanded (Figure 19.18).
- **Single-package, variable-volume**, which consists of several controlled spaces served by one unit. Supply air from the unit is at a constant temperature, with air volume to each space varied to satisfy space demands (Figure 19.19).
- **Multisplit,** which consists of several controlled spaces, each served by a separate indoor unit. All indoor units are connected to an outdoor condensing unit (Figure 19.20). When each indoor unit varies its refrigerant flow in response to heating or cooling load demand, the system is called **variable refrigerant flow (VRF)**.

In general, roof-mounted single-package unitary equipment is limited to five or six stories because duct space and available blower power become excessive in taller buildings. Split units are limited by the maximum distance allowed between the indoor and outdoor sections because of losses in refrigerant piping, compressor capability, and refrigerant oil management. Indoor, single-zone equipment is generally less expensive to maintain and service than multizone or multisplit units.

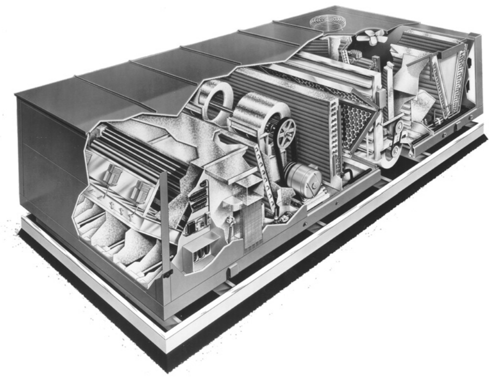


Figure 19.18 Typical Rooftop Air-Cooled Single-Package Air Conditioner [2016S, Ch 49, Fig 1]

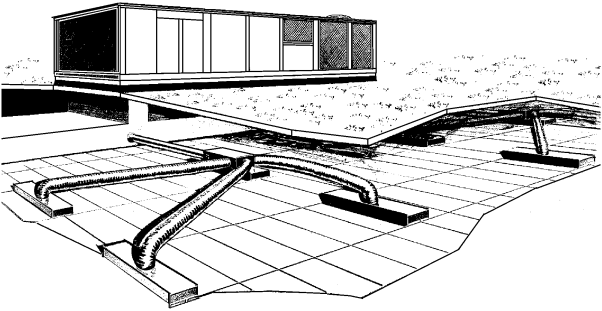


Figure 19.19 Single-Package Air Equipment with Variable Air Volume [2016S, Ch 49, Fig 2]

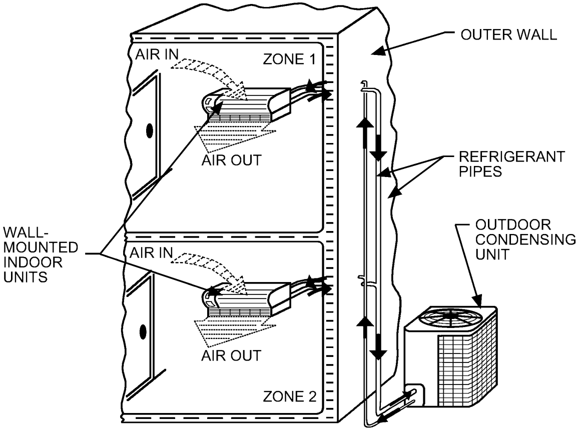


Figure 19.20 Example of Two-Zone Ductless Multisplit System in Typical Residential Installation [2016S, Ch 49, Fig 3]

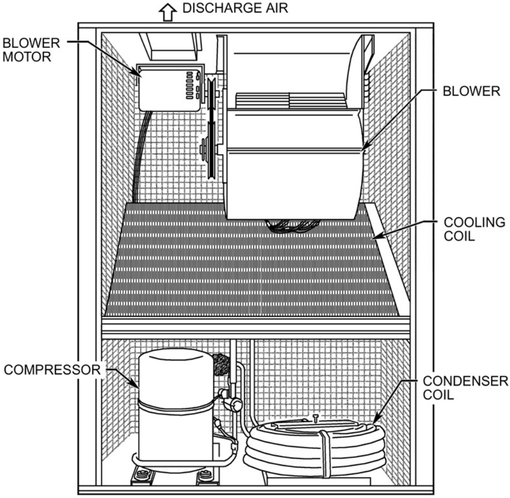


Figure 19.21 Water-Cooled Single-Package Air Conditioner [2016S, Ch 49, Fig 4]

Manufacturers' literature has detailed information about geometry, performance, electrical characteristics, application, and operating limits. The system designer selects suitable equipment with the capacity for the application.

Unitary equipment is designed to keep installation costs low. Adequate planning is important for installing large, roof-mounted equipment because special rigging equipment is frequently required. ACCA Standard 5 describes minimum criteria for the proper installation of HVAC systems in residential and commercial installations.

An advantage of packaged unitary equipment is that proper installation minimizes the risk of field contamination of the circuit. Care must be taken to properly install split-system interconnecting tubing (e.g., proper cleanliness, brazing, and evacuation to remove moisture and other noncondensables). Split systems should be charged according to the manufacturer's instructions. Filter-driers are necessary; if they are not installed at the factory, they should be field installed. When installing split, multisplit, and VRF systems, lines must be properly routed and sized to ensure proper oil return to the compressor.

Unitary equipment must be located to avoid noise and vibration problems. Single-package equipment of over 70 kW capacity should be mounted on concrete pads if vibration control is a concern. Large-capacity equipment should be roof mounted only after the roof's structural adequacy has been evaluated. If they are located over occupied space, roof-mounted units with return fans that use ceiling space for the return plenum should have a lined return plenum according to the manufacturer's recommendations. Use duct silencers where low sound levels are desired. Mass and sound data are available from many manufacturers. Additional installation guidelines include the following:

- In general, install products containing compressors on solid, level surfaces.
- Avoid mounting products containing compressors (such as remote units) on or touching the foundation of a house or building, or outside bedroom windows. A separate pad that does not touch the foundation is recommended to reduce any noise and vibration transmission through the slab.

- Do not box in outdoor air-cooled units with fences, walls, overhangs, or bushes. Doing so reduces the air-moving capability of the unit, reducing efficiency. Manufacturers include minimum clearances in literature.
- For a split-system remote unit, choose an installation site that is close to the indoor part of the system to minimize pressure drop in the connecting refrigerant tubing. Comply with manufacturers' refrigerant line length limits and required accessories listed in their literature.
- For VRF units, locate the refrigerant pipes' headers so that the length of refrigerant pipes is minimized.
- Contact the manufacturer or consult installation instructions for further information on installation procedures.

Unitary equipment should be listed or certified by nationally recognized testing laboratories to ensure safe operation and compliance with government and utility regulations. Equipment should also be installed to comply with agency standards' rating and application requirements to ensure that it performs according to industry criteria. Larger and more specialized equipment often does not carry agency labeling. However, power and control wiring practices should comply with the *National Electrical Code*® (NFPA Standard 70). Consult local codes before the installation is designed, and consult local inspectors before installation.

Unitary air conditioners have factory-matched refrigerant circuit components that are applied in the field to fulfill the user's requirements. The manufacturer often incorporates a heating function compatible with the cooling system and a control system that requires minimal field wiring.

Products are available to meet the objectives of nearly any system. Many different heating sections (gas- or oil-fired, electric, or condenser reheat), air filters, and heat pumps, which are a specialized form of unitary product, are available. Such matched equipment, selected with compatible accessory items, requires little field design or field installation work.

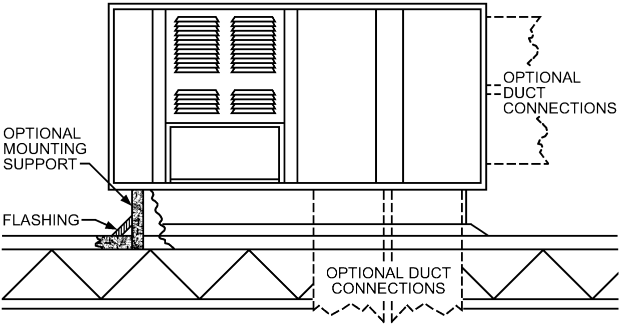


Figure 19.22 Rooftop Installation of Air-Cooled Single-Package Unit [2016S, Ch 49, Fig 5]

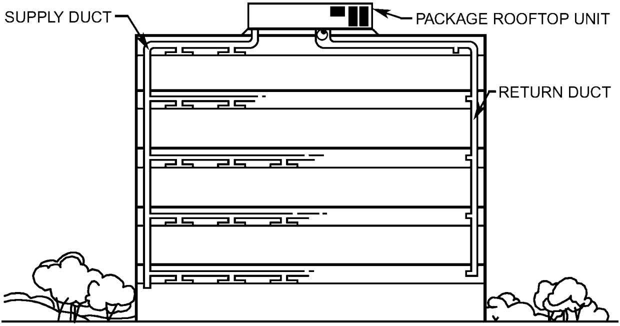


Figure 19.23 Multistory Rooftop Installation of Single-Package Unit [2016S, Ch 49, Fig 6]

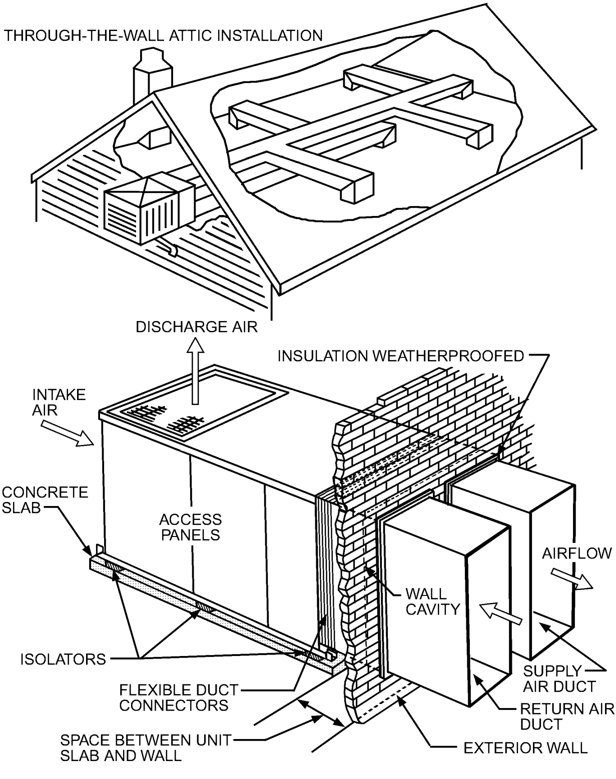


Figure 19.24 Through-the-Wall Installation of Air-Cooled Single-Package Unit
[2016S, Ch 49, Fig 7]

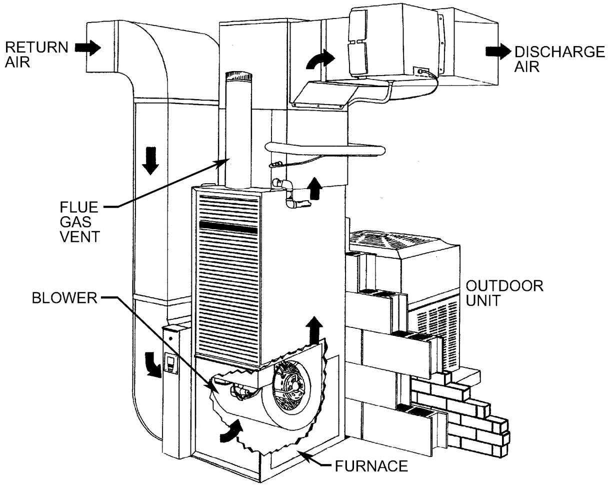


Figure 19.25 Residential Installation of Split-System Air-Cooled Condensing Unit with Coil and Upflow Furnace [2016S, Ch 49, Fig 8]

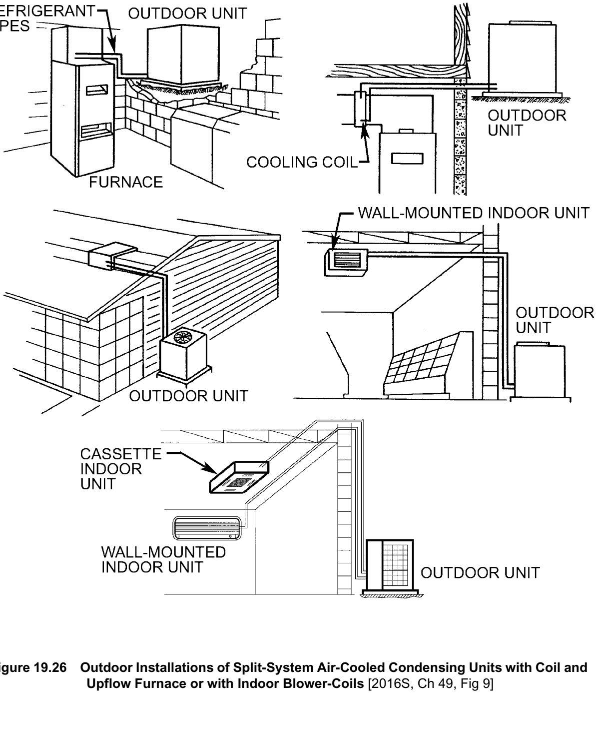


Figure 19.26 Outdoor Installations of Split-System Air-Cooled Condensing Units with Coil and Upflow Furnace or with Indoor Blower-Coils [2016S, Ch 49, Fig 9]

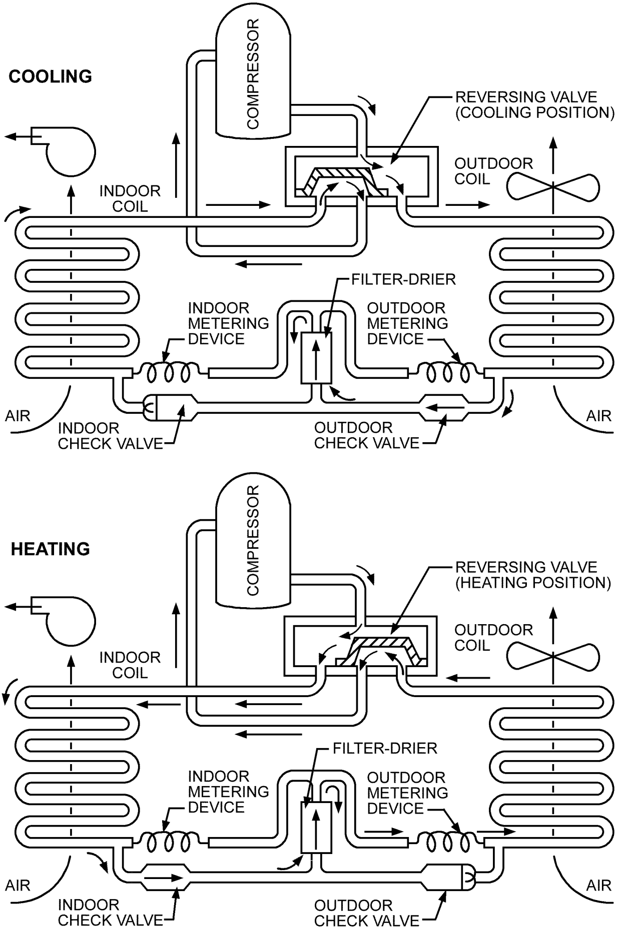


Figure 19.27 Schematic Typical of Air-to-Air Heat Pump System [2016S, Ch 49, Fig 12]

Evaporative Cooling

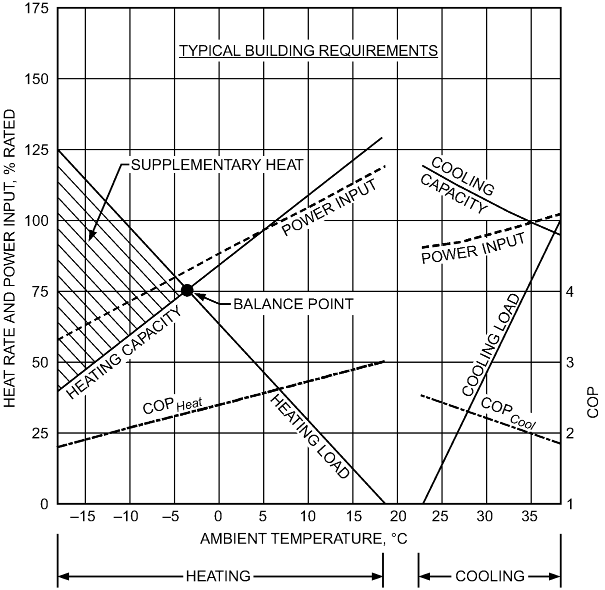


Figure 19.28 Operating Characteristics of Single-Stage Unmodulated Heat Pump
[2016S, Ch 49, Fig 13]

Water-Source Heat Pumps

A water-source heat pump (WSHP) is a single-package reverse-cycle heat pump that uses water as the heat source for heating and as the heat sink for cooling. The water supply may be a recirculating closed loop, a well, a lake, or a stream. Water for closed-loop heat pumps is usually circulated at 36 to 54 mL/s per kilowatt of cooling capacity.

WSHPs are used in a variety of systems, such as the following:

A **water-loop heat pump (WLHP)** uses a circulating water loop as the heat source and heat sink. When loop water temperature exceeds a certain level during cooling, a cooling tower dissipates heat from the water loop into the atmosphere. When loop water temperature drops below a prescribed level during heating, heat is added to the circulating loop water, usually with a boiler. In multiple-unit installations, some heat pumps may operate in cooling mode while others operate in heating, and controls are needed to keep loop water temperature within the prescribed limits. Chapter 9 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment* has more information on water-loop heat pumps.

A **groundwater heat pump (GWHP)** passes groundwater from a nearby well through the heat pump's water-to-refrigerant heat exchanger, where it is warmed or cooled, depending on the operating mode. It is then discharged to a drain, stream, or lake, or is returned to the ground through a reinjection well.

Many state and local jurisdictions have ordinances about use and discharge of groundwater. Because aquifers, the water table, and groundwater availability vary from region to region, these regulations cover a wide spectrum.

A **surface-water heat pump (SWHP)** uses water from a nearby lake, stream, or canal. After passing through the heat pump heat exchanger, it is returned to the source or a drain several degrees warmer or cooler, depending on the operating mode of the heat pump. **Closed-loop** surface water heat pumps use a closed water or brine loop that includes pipes or tubing submerged in the surface water (river, lake, or large pond) that serves as the heat exchanger. The adequacy of the total thermal capacity of the body of water must be considered.

A **ground-coupled heat pump (GCHP), ground-source heat pump (GSHP),** or **geothermal heat pump (GHP)** system uses the earth as a heat source and sink. Usually, plastic piping is installed in either a shallow horizontal or deep vertical array to form the heat exchanger. The massive thermal capacity of the earth provides a temperature-stabilizing effect on the circulating loop water or brine. Installing this type of system requires detailed knowledge of the climate; site; soil temperature, moisture content, and thermal characteristics; and performance, design,

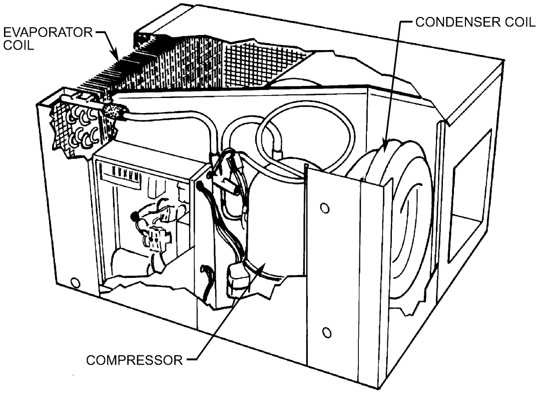


Figure 19.29 Typical Horizontal Water-Source Heat Pump [2016S, Ch 49, Fig 15]

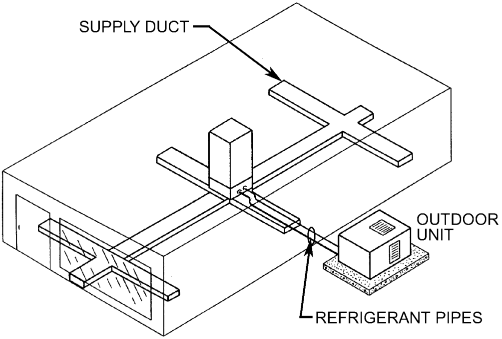


Figure 19.30 Outdoor Installation of Split-System Air-Cooled Condensing Unit with Indoor Coil and Downflow Furnace [2016S, Ch 49, Fig 10]

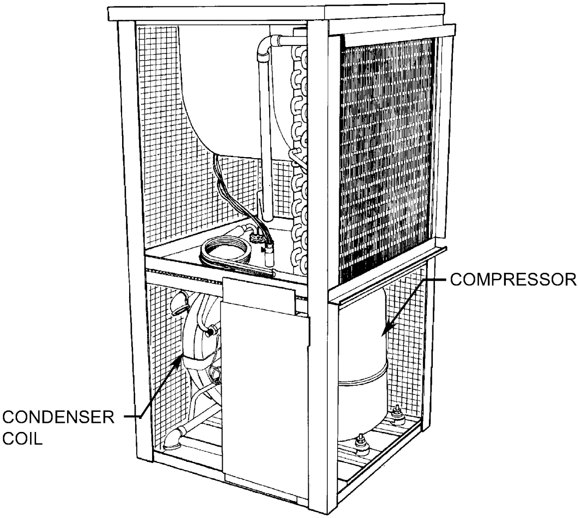
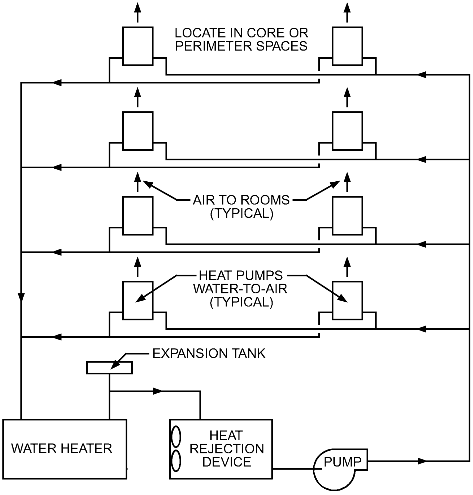
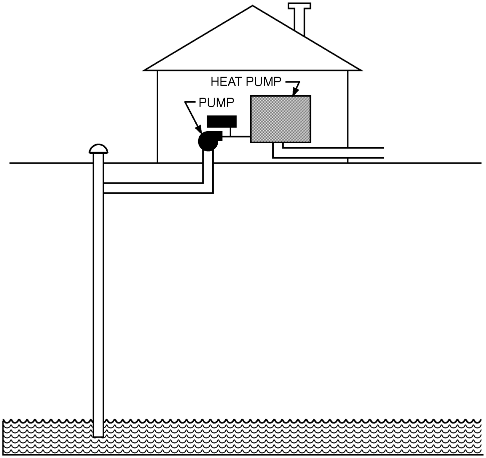


Figure 19.31 Typical Vertical Water-Source Heat Pump [2016S, Ch 49, Fig 16]



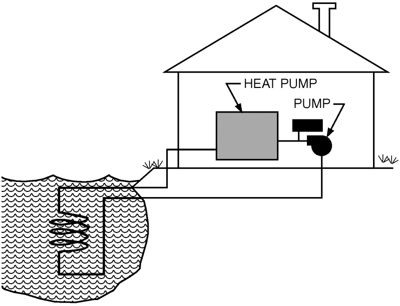
A. WATER-LOOP HEAT PUMP SYSTEM



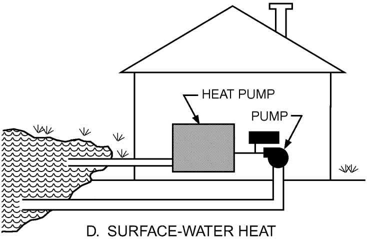
B. GROUNDWATER HEAT PUMP SYSTEM

Figure 19.32 Water-Source Heat Pump Systems [2016S, Ch 49, Fig 17]

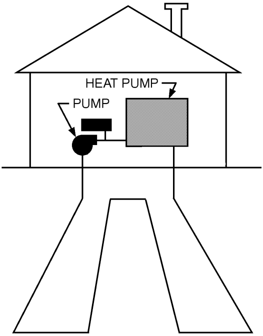
Evaporative Cooling



C. CLOSED-LOOP SURFACE-WATER HEAT PUMP SYSTEM



D. SURFACE-WATER HEAT PUMP SYSTEM



E. GROUND-COUPLED HEAT PUMP SYSTEM

Figure 19.32 Water-Source Heat Pump Systems [2016S, Ch 49, Fig 17]
(Continued)

and installation of water-to-earth heat exchangers. Additional information on GCHP systems is presented in Chapter 34 of the 2015 *ASHRAE Handbook—HVAC Applications*.

Entering Water Temperatures. These various water sources provide a wide range of entering water temperatures to WSHPs. Entering water temperatures vary not only by water source, but also by climate and time of year. Because of the wide range of entering water or brine temperatures encountered, it is not feasible to design a universal packaged product that can handle the full range of possibilities effectively. Therefore, WSHPs are rated for performance at a number of standard rating conditions.

Compressors. WSHPs usually have single-speed compressors, although some high-efficiency models use multispeed compressors. Higher-capacity equipment may use multiple compressors. Compressors may be reciprocating, rotary, or scroll. Single-phase units are available at voltages of 115, 208, 230, and 265. All larger equipment is for three-phase power supplies with voltages of 208, 230, 460, or 575. Compressors usually have electromechanical protective devices.

Indoor Air System. Console WSHP models are designed for free delivery of conditioned air. Other models have ducting capability. Smaller WSHPs have multispeed, direct-drive centrifugal blower wheel fan systems. Large-capacity equipment has belt-drive systems. All units have provisions for fiberglass, metal, or plastic foam air filters.

Indoor Air Heat Exchanger. The indoor air heat exchanger of WSHP units is usually a conventional plate-fin coil of copper tubes and aluminum fins. Microchannel evaporators are also used in some products. The indoor air heat exchanger must be circuited so that it can function effectively as an evaporator with refrigerant flow in one direction and as a condenser when refrigerant flow is reversed.

Refrigerant-to-Water Heat Exchanger. The heat exchanger, which couples the heat pump to source/sink water, is tube-in-tube, tube-in-shell, or brazed-plate. It must function in either condensing or evaporating mode, so special attention is given to refrigerant-side circuitry. Heat exchanger construction is usually of copper and steel, and the source/sink water is exposed only to the copper portions. Cupronickel options to replace the copper are usually available for use with brackish or corrosive water. Brazed-plate heat exchangers are usually constructed of stainless steel, which reduces the need for special materials.

Refrigerant Expansion Devices. These WSHPs operate over a narrow range of entering water temperatures and typically use simple capillaries as expansion devices. However, units may also use thermostatic expansion valves for improved performance over a broader range of inlet fluid temperatures.

Refrigerant-Reversing Valve. The refrigerant-reversing valves in WSHPs are identical to those used in air-source heat pumps.

Condensate Disposal. Condensate, which forms on the indoor coil when cooling, is collected and conveyed to a drain system.

Controls. Console WSHP units have built-in operating mode selector and thermostatic controls. Ducted units use low-voltage remote heat/cool thermostats.

Size. Typical space requirements and masses of WSHPs are presented in Table 19.4.

Special Features. Some WSHPs include the following:

Desuperheater. Uses discharge gas in a special water/refrigerant heat exchanger to heat water for a building.

Capacity modulation. May use multiple compressors, multispeed compressors, or hot-gas bypass.

Variable air volume (VAV). Reduces fan energy usage and requires some form of capacity modulation.

Automatic water valve. Closes off water flow through the unit when the compressor is off and allows variable water volume in the loop, which reduces pumping energy.

Outdoor air economizer. Cools directly with outdoor air to reduce or eliminate the need for mechanical refrigeration during mild or cold weather when outdoor humidity levels and air quality are appropriate.

Water-side economizer. Cools with loop water to reduce or eliminate the need for mechanical refrigeration during cold weather; requires a hydronic coil in the indoor air circuit that is valved into the circulating loop when loop temperatures are relatively low and cooling is required.

Electric heaters. Used in WLHP systems that do not have a boiler as a source for loop heating.

Table 19.4 Space Requirements for Typical Packaged Water-Source Heat Pumps [2016S, Ch 49, Tbl 3]

Water-to-Air Heat Pump	Length × Width × Height, m	Mass, kg
5 kW vertical unit	0.6 × 0.6 × 0.9	80
10 kW vertical unit	0.8 × 0.8 × 1.2	110
10 kW horizontal unit	1.1 × 0.6 × 0.6	110
15 kW vertical unit	0.9 × 0.8 × 1.2	150
40 kW vertical unit	1.1 × 0.9 × 1.8	330
90 kW vertical unit	1.1 × 1.5 × 1.8	700

Note: See manufacturers' specification sheets for actual values.

Variable-Refrigerant-Flow Heat Pumps

A variable-refrigerant-flow (VRF) system typically consists of a condensing section housing compressor(s) and condenser heat exchanger interconnected by a single set of refrigerant piping to multiple indoor direct-expansion (DX) evaporator fan-coil units. Thirty or more DX fan-coil units can be connected to a single condensing section, depending on system design, and with capacity ranging from 2 to 30 kW.

The DX fan-coils are constant air volume, but use variable refrigerant flow through an electronic expansion valve. The electronic expansion valve reacts to several temperature-sensing devices such as return air, inlet and outlet refrigerant temperatures, or suction pressure. The electronic expansion valve modulates to maintain the desired set point.

Application. VRF systems are most commonly air-to-air, but are also available in a water-source (water-to-refrigerant) configuration. They can be configured for simultaneous heating and cooling operation (some indoor fan-coil units operating in heating and some in cooling, depending on requirements of each building zone).

Indoor units are typically direct-expansion evaporators using individual electronic expansion devices and dedicated microprocessor controls for individual control. Each indoor unit can be controlled by an individual thermostat. The outdoor unit may connect several indoor evaporator units with capacities 130% or more than the outdoor condensing unit capacity.

Categories. VRF equipment is divided into three general categories: residential, light commercial, and applied. Residential equipment is single-phase unitary equipment with a cooling capacity of 19 kW or less. Light commercial equipment is generally three-phase, with cooling capacity greater than 19 kW, and is designed for small businesses and commercial properties. Applied equipment has cooling capacity higher than 40 kW and is designed for large commercial buildings.

Refrigerant Circuit and Components. VRF heat pump systems use a two-pipe (liquid and suction gas) system; simultaneous heat and cool systems use the same system, as well as a gas flow device that determines the proper routing of refrigerant gas to a particular indoor unit.

VRF systems use a sophisticated refrigerant circuit that monitors mass flow, oil flow, and balance to ensure optimum performance. This is accomplished in unison with variable-speed compressors and condenser fan motors. Both of these components adjust their frequency in reaction to changing mass flow conditions and refrigerant operating pressures and temperatures. A dedicated microprocessor continuously monitors and controls these key components to ensure proper refrigerant is delivered to each indoor unit in cooling or heating.

Heating and Defrost Operation. In heating mode, VRF systems typically must defrost like any mechanical heat pump, using reverse-cycle valves to temporarily operate the outdoor coil in cooling mode. Oil return and balance with the refrigerant circuit is managed by the microprocessor to ensure that any oil entrained in the low side of the system is brought back to the high side by increasing the refrigerant velocity using a high-frequency operation performed automatically based on hours of operation.

More information on VRF heat pumps can be found in Chapter 18 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*, and information on performance-rating these systems can be found in AHRI Standard 1230-2010.

Room Air Conditioners and Packaged Terminal Air Conditioners

Room Air Conditioners

Room air conditioners are encased assemblies designed prima-rily for mounting in a window or through a wall. They are designed to deliver cool or warm conditioned air to the room, either without ducts or with very short ducts (up to a maximum of about 1200 mm). Each unit includes a prime source of refrigeration and dehumidification and a means for circulating and filtering air; it may also include a means for ventilating and/or exhausting and heating.

The basic function of a room air conditioner is to provide comfort by cooling, dehumidifying, filtering or cleaning, and circulating the room air. It may also provide ventilation by introducing outdoor air into the room and/or exhausting room air to the outdoors. Room temperature may be controlled by an integral thermostat. The conditioner may provide heating by heat pump operation, electric resistance elements, or a combination of the two.

Figure 19.33 shows a typical room air conditioner in cooling mode. Warm room air passes over the cooling coil and transfers sensible and latent heat. The conditioned air is then recirculated in the room by a fan or blower.

Heat from the warm room air vaporizes the cold (low-pressure) liquid refrigerant flowing through the evaporator. The vapor then carries the heat to the compressor, which compresses the vapor and increases its temperature above that of the outdoor air. In the condenser, the hot (high-pressure) refrigerant vapor liquefies, transferring the heat from the room air to outdoor air. Next, the high-pressure liquid refrigerant passes through a restrictor, which reduces its pressure and temperature. The cold (low-pressure) liquid refrigerant then enters the evaporator to repeat the refrigeration cycle.

Room air conditioners have line cords, which may be plugged into standard or special electric circuits. Most units in the United States are designed to operate at 115, 208, or 230 V; single-phase; 60 Hz power. Some units are rated at 265 V or 277 V, for which the chassis or chassis assembly must provide permanent electrical connection. The maximum amperage of 115 V units is generally 12 A, which is the maximum current permitted by NFPA Standard 70 [the *National Electrical Code*® (NEC)] for a single-outlet, 15 A circuit. Models designed for countries other

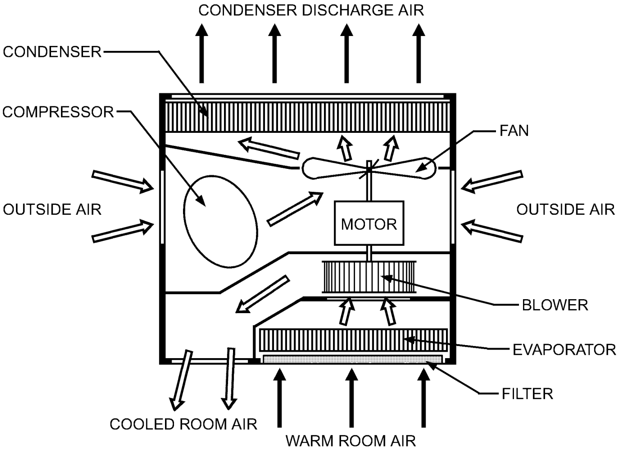


Figure 19.33 Schematic View of Typical Room Air Conditioner [2016S, Ch 50, Fig 1]

than the United States are generally for 50 or 60 Hz systems, with typical design voltage ranges of 100 to 120 and 200 to 240 V, single-phase.

Popular 115 V models have capacities in the range of 1.5 to 2.3 kW, and are typically used in single-room applications. Larger-capacity 115 V units are in the 3.5 to 4.4 kW range. Capacities for 230, 208, or 230/208 V units range from 2.3 to 10.6 kW. These higher-voltage units are typically used in multiple-room installations.

Heat pump models are also available, usually for 208 or 230 V applications. These units are generally designed for reversed-refrigerant-cycle operation as the normal means of supplying heat, but may incorporate electrical-resistance heat either to supplement heat pump capacity or to provide the total heating capacity when outdoor temperatures drop below a set value.

Another type of heating model incorporates electrical heating elements in regular cooling units so that heating is provided entirely by electrical resistance heat.

Installation procedures vary because units can be mounted in various ways. It is important to select the mounting for each installation that best satisfies the user and complies with applicable building codes. Common mounting methods include the following:

- **Indoor flush mounting.** Interior face of conditioner is approximately flush with inside wall.
- **Balance mounting.** Unit is approximately half inside and half outside window.
- **Outdoor flush mounting.** Outer face of unit is flush with or slightly beyond outside wall.
- **Special mounting.** Examples include casement windows, horizontal sliding windows, and office windows with swinging units (or swinging windows) to allow window washing, and transoms over doorways.
- **Through-the-wall mounts or sleeves.** This mounting is used for installing window-type chassis, complete units, or consoles in walls of apartment buildings, hotels, motels, and residences. Although very similar to window-mounted units, through-the-wall models do not have side louvers for condenser air; air comes from the outdoor end of the unit.

Room air conditioners have become more compact to minimize both loss of window light and projection inside and outside the structure. Several types of expandable mounts are now available for fast, dependable installation in single- and double-hung windows, as well as in horizontal sliding windows. Window air conditioners should fit in the opening without too much space around the sides; most units come with accordion-style flaps attached to the sides, used to fill the open space around the unit. Installation kits include all parts needed for structural mounting, such as gaskets, panels, and seals for weathertight assembly. Sealing the space around the unit (e.g., with caulk or foam seals) is important to prevent air from escaping and limit seeping of hot outdoor air into the conditioned space, and to achieve energy savings during operation.

Adequate wiring and proper breakers or fuses must be provided for the service outlet. Necessary information is usually given on instruction sheets or stamped on the air conditioner near the service cord or on the serial plate. It is important to follow the manufacturer's recommendation for size and type of breaker or fuse. All units are equipped by the manufacturer with grounding plug caps on the service cord. Receptacles with grounding contacts correctly designed to fit these plug caps should be used when units are installed.

Units rated 265 or 277 V must provide for permanent electrical connection with armored cable or conduit to the chassis or chassis assembly. Manufacturers usually provide an adequate cord and plug cap in the chassis assembly to facilitate installation and service.

One type of room air conditioner is the integral chassis design, with the outer cabinet fastened permanently to the chassis. Most electrical components can be serviced by partially dismantling the control area without removing the unit from the installation. Another type is the **slide-out chassis** design, which allows the outer cabinet to remain in place while the chassis is removed for service.

Effective condensate management should be considered during the installation of the air conditioner. Many window air conditioners have connection points for condensate drains. Follow plumbing and building code requirements for handling discharge of the condensate produced when the air conditioner is operating.

Packaged Terminal Air Conditioners

A packaged terminal air conditioner (PTAC) includes a wall sleeve and a separate unencased combination of heating and cooling assemblies intended for mounting through the wall. A PTAC includes refrigeration components, separable outdoor louvers, forced ventilation, and heating by hot water, steam, or electric resistance. PTAC units with indirect-fired gas heaters are also available from some manufacturers. A packaged terminal heat pump (PTHP) is a heat pump version of a PTAC that provides heat with a reverse-cycle operating mode. A PTHP should provide a supplementary heat source, which can be hot water, steam, electric resistance, or another source.

PTACs are designed primarily for commercial installations to provide the total heating and cooling functions for a room or zone and are specifically for through-the-wall installation. The units are mostly used in relatively small zones on the perimeter of buildings such as hotels and motels, apartments, hospitals, nursing homes, and office buildings. In larger buildings, they may be combined with nearly any system selected for environmental control of the building core.

PTACs and PTHPs are similar in design and construction. The most apparent difference is the addition of a refrigerant-reversing valve in the PTHP. Optional components that control the heating functions of the heat pump include an outdoor thermostat to signal the need for changes in heating operating modes, and, in more complex designs, frost sensors, defrost termination devices, and base pan heaters.

PTACs/PTHPs are available in a wide range of rated cooling capacities, typically 1.7 to 5.3 kW, with comparable levels of heating output. Units are available as sectional types or integrated types. A sectional-type unit (Figure 19.34) has a separate cooling chassis; an integrated-type unit (Figure 19.35) has an electric or a gas heating option added to the chassis. Hot-water or steam heating options are usually part of the cabinet or wall box. Both types include the following:

- Heating elements available in hot water, steam, electric, or gas heat
- Integral or remote temperature and operating controls
- Wall sleeve or box
- Removable (or separable) outdoor louvers
- Room cabinet
- Means for controlled forced ventilation
- Means for filtering air delivered to the room

PTAC assemblies are intended for use in free conditioned-air distribution, but a particular application may require minimal ductwork with a total external static resistance up to 25 Pa.

Packaged terminal air conditioners and packaged terminal heat pumps allow the HVAC designer to integrate the exposed outdoor louver or grille with the building design. Various grilles are available to blend with or accent most construction materials. Because the product becomes part of the building's facade, the architect must consider the product during the conception of the building. Wall sleeve installation is usually done by ironworkers, masons, or carpenters. All-electric units dominate the market.

All the energy of all-electric versions is dispersed through the building via electrical wiring, so the electric designer and electrical contractor play a major role. Final installation is reduced to sliding in the chassis and plugging the unit into an adjacent receptacle. For these all-electric units, the traditional HVAC contractor's work involving ducting, piping, and refrigeration systems is bypassed. This results in a low-cost installation and allows installation of the PTAC/PTHP chassis to be deferred until just before occupancy.

When comparing a gas-fired PTAC to a PTAC with electric resistance heat or a PTHP, evaluate both operating and installation costs. Generally, a gas-fired PTAC is more expensive to install but less expensive to operate in heating mode. A life-cycle cost comparison is recommended (see Chapter 37 of the 2015 *ASHRAE Handbook—HVAC Applications*).

One main advantage of the PTAC/PTHP concept is that it provides excellent zoning capability. Units can be shut down or operated in a holding condition during unoccupied periods. Present equipment efficiency-rating criteria are based on full-load operation, so an efficiency comparison to other approaches may suffer.

The designer must also consider that total capacity is the sum of the peak loads of each zone rather than the peak load of the building. Therefore, total cooling capacity of the zonal system will exceed that of a central system.

Because PTAC units are located in the conditioned space, both appearance and sound level of the equipment are important considerations. Sound attenuation in ducting is not available with the free-discharge PTAC units.

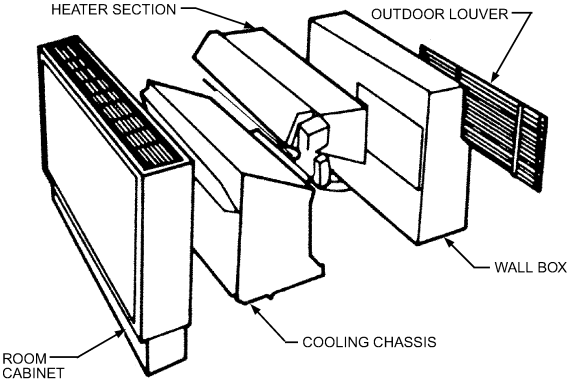


Figure 19.34 Sectional Packaged Terminal Air Conditioner [2016S, Ch 50, Fig 2]

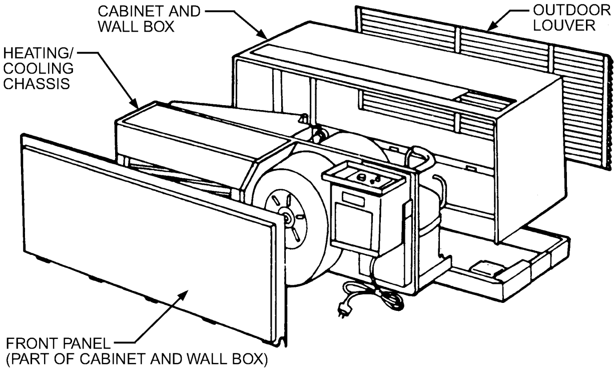


Figure 19.35 Integrated Packaged Terminal Air Conditioner [2016S, Ch 50, Fig 3]

The designer must also consider the added infiltration and thermal leakage load resulting from perimeter wall penetrations. These losses are accounted for during the *on* cycle in equipment cooling ratings and PTHP heating ratings, but during the *off* cycle or with other forms of heating, they could be significant.

Most packaged terminal equipment is designed to fit into a wall aperture approximately 1100 mm wide and 400 mm high. Although unitary products can increase in size with increasing cooling capacity, PTAC/PTHP units, regardless of cooling capacity, are usually constrained to a few cabinet sizes. The exterior of the equipment must be essentially flush with the exterior wall to meet most building codes. In addition, cabinet structural requirements and the slide-in chassis reduce the available area for outdoor air inlet and relief to less than a total of 0.33 m^2. Manufacturers' specification sheets should be consulted for more accurate and detailed information.

Basic PTHP units can operate in heat pump mode until outdoor temperature is just above the point at which the outdoor heat exchanger would frost. At that point, heat pump mode is locked out, and other forms of heating are required. Some units include two-stage indoor thermostats and automatically switch from heat pump mode to an alternative heat source if space temperature drops too far below the first-stage set point. Some PTHPs use control schemes that extend heat pump operation to lower temperatures. One approach allows heat pump operation down to outdoor temperatures just above freezing. If the outdoor coil frosts, it is defrosted by shutting down the compressor and allowing the outdoor fan to continue circulating outdoor air over the coil. Another approach allows heat pump operation to even lower outdoor temperatures by using a reverse-cycle defrost sequence. In those cases, the heat pump mode is usually locked out for outdoor temperatures below –12°C.

EVAPORATIVE COOLING

Direct Evaporative Air Coolers

Air is drawn through porous wetted pads or a spray, or rigid media; and its sensible heat energy evaporates some water. The heat and mass transfer between the air and water lowers the air dry-bulb temperature and increases the humidity at a constant wet-bulb temperature. The dry-bulb temperature of the nearly saturated air approaches the ambient air's wet-bulb temperature. The process is adiabatic, so no sensible cooling occurs.

The extent to which the leaving air temperature from a direct evaporative cooler approaches the thermodynamic wet-bulb temperature of the entering air or the extent to which complete saturation is approached is expressed as the **direct saturation efficiency**, defined as

$$\varepsilon_e = 100\frac{t_1 - t_2}{t_1 - t_s'} \tag{19.13}$$

where

ε_e	=	direct evaporative cooling or saturation efficiency, %
t_1	=	dry-bulb temperature of entering air, °C
t_2	=	dry-bulb temperature of leaving air, °C
t_s'	=	thermodynamic wet-bulb temperature of entering air, °C

An efficient wetted pad can reduce the air dry-bulb temperature by as much as 95% of the wet-bulb depression (ambient dry-bulb temperature less wet-bulb temperature), while an inefficient and poorly designed pad may only reduce this by 50% or less.

Direct evaporative cooling, though simple and inexpensive, has the disadvantage that if the ambient wet-bulb temperature is higher than about 21°C, the cooling effect is not sufficient for indoor comfort but still may be sufficient for relief cooling applications. Direct evaporative coolers should not recirculate indoor air.

Fifty mm pad coolers, usually small capacity, operate at 0.50 to 1.25 m/s face velocity. 300 mm-deep rigid media larger coolers operate at 2 to 3 m/s face velocity and have higher saturation efficiencies.

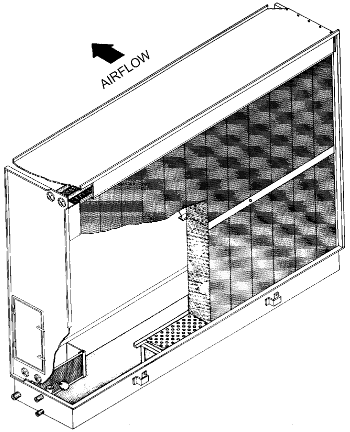


Figure 19.36 Rigid Media Direct Evaporative Cooler [2016S, Ch 41, Fig 2]

Indirect Evaporative Air Coolers

In indirect evaporative air coolers, outdoor air or exhaust air from the conditioned space passes through one side of a heat exchanger. This secondary airstream is cooled by evaporation by direct wetting of the heat exchanger surface, or passing through evaporative cooling media, atomizing spray, or disk evaporator. The surfaces of the heat exchanger are cooled by the secondary airstream. On the other side of the heat exchanger surface, the primary airstream (conditioned air to be supplied to the space) is sensibly cooled.

Although the primary air is cooled by secondary air, no moisture is added to the primary air. Because the enthalpy of the primary air decreases, the leaving dry-bulb temperature of the primary air must always be above the entering wet-bulb temperature of the secondary airstream. Dehumidifying in the primary airstream can occur only when the dew point of the primary airstream is several degrees higher than the wet-bulb temperature of the secondary air-stream. This condition exists only when the secondary airstream is drier than the primary airstream, such as when building exhaust air is used for the secondary air.

Indirect evaporative cooling efficiency, or **wet-bulb depression efficiency (WBDE),** is defined as

$$\text{WBDE} = 100\frac{t_1 - t_2}{t_1 - t'_s} \tag{19.14}$$

where

WBDE	=	indirect evaporative cooling efficiency,%
t_1	=	dry-bulb temperature of entering primary air, °C
t_2	=	dry-bulb temperature of leaving primary air, °C
t_s'	=	wet-bulb temperature of entering secondary air, °C

In a two-stage indirect/direct evaporative cooler, a first-stage indirect evaporative cooler lowers both the dry- and wet-bulb temperature of the incoming air. After leaving the indirect stage, the supply air passes through a second-stage direct evaporative cooler.

This method can lower the supply air dry-bulb temperature by 6K or more below the secondary air wet-bulb temperature.

In areas with a higher wet-bulb design temperature or where the design requires a supply air temperature lower than that attainable using indirect/direct evaporative cooling, a third cooling stage may be required. This stage may be a direct-expansion refrigeration unit or a chilled-water coil located either upstream or downstream from the direct evaporative cooling stage, but always downstream from the indirect evaporative stage.

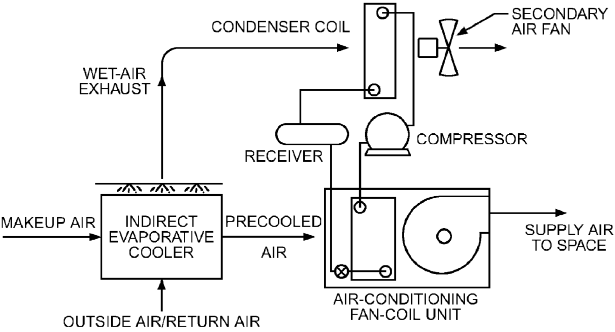


Figure 19.37 Indirect Evaporative Cooler Used as Precooler [2016S, Ch 41, Fig 4]

Table 19.5 Indirect Evaporative Cooling Systems Comparison

System Type[a]	WBDE,[b] %	Heat Recovery Efficiency, %	Wet-Side Air ΔP, Pa	Dry-Side Air ΔP, Pa	Pump Power, W per 4720 L/s	Parasitic Loss Range,[e] W/3517 W of Cooling	Notes
Cooling tower to coil	40 to 60	NA	NA	99.5 to174.1	Varies	Varies	Best for serving multiple AHUs from a single cooling tower. No winter heat recovery.
Crossflow plate	60 to 85	40 to 50	174.2 to 248.8	99.5 to174.1	74.6 to149.2	120 to 200	Most cost-effective for lower airflows. Some cross contamination possible. Low winter heat recovery.
Heat pipe[c]	65 to 75	50 to 60	174.2 to248.8	124.4 to174.1	149.2 to 298.4	150 to 259	Most cost-effective for large airflows. Some cross contamination possible. Medium winter heat recovery.
Heat wheel[d]	60 to 70	70 to 80	149.3 to 223.9	99.5 to161.7	74.6 to149.2	200 to 300	Best for high airflows. Some cross contamination. Highest winter heat recovery rates.
Runaround coil[δ]	35 to 50	40 to 60	149.3 to 199.0	99.5 to161.7	Varies	> 350	Best for applications where supply and return air ducts are separated. Lowest summer WBDE.

WBDE = wet-bulb depression efficiency

Notes:
[a]All air-to-air heat exchangers have equal mass flow on supply and exhaust sides.
[b]Plate and heat pipe are direct spray on exhaust side. Heat wheel and runaround coil systems use 90% WBDE direct evaporative cooling media on exhaust air side.
[c]Assumes six-row heat pipe, 2.3 mm fin spacing, with 2.54 m/s face velocity on both sides.
[d]Assumes 2.54 m/s face velocity. Parasitic loss includes wheel rotational power.
[e]Includes air-side static pressure and pumping penalty.

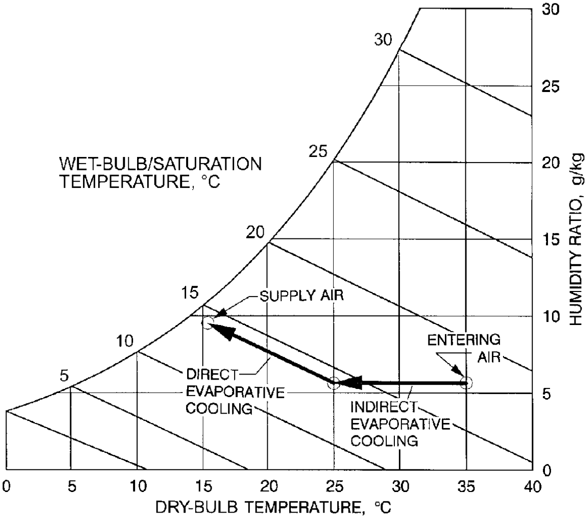


Figure 19.38 Two-Stage Indirect/Direct Evaporative Cooling Process [2016S, Ch 41, Fig 6]

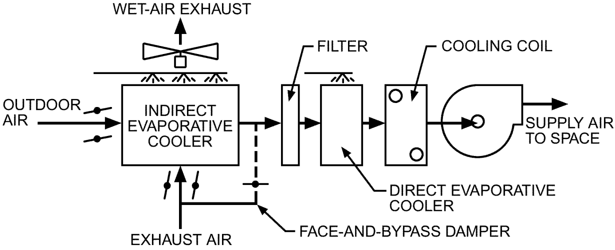


Figure 19.39 Three-Stage Indirect/Direct Evaporative Cooler [2016S, Ch 41, Fig 8]

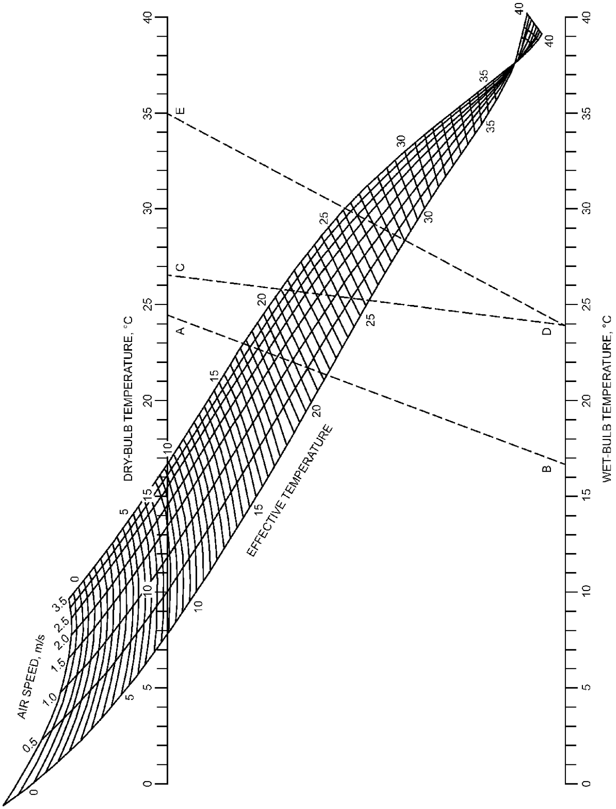


Figure 19.40 Effective Temperature Chart [2015A, Ch 52, Fig 14]

20. AUTOMATIC CONTROLS

HVAC System Components

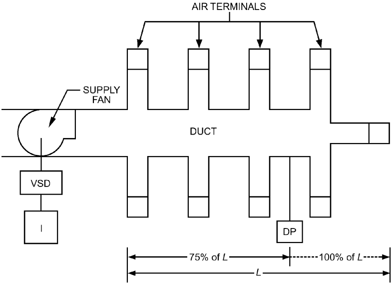


Figure 20.1 Duct Static Pressure Control [2015A, Ch 47, Fig 15]

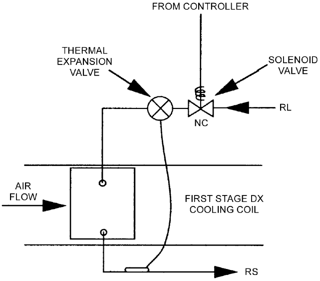


Figure 20.2 Direct Expansion—Two-Position Control

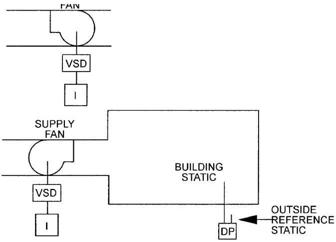


Figure 20.3 Duct Static Control of Return Fan

Automatic Controls

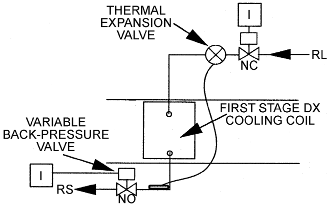


Figure 20.4 Modulating Direct-Expansion Cooling

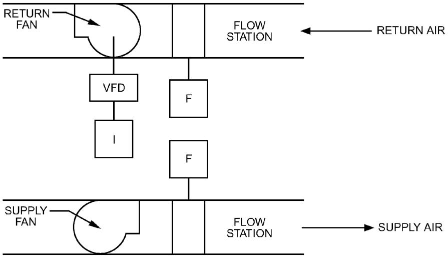


Figure 20.5 Airflow Tracking Control [2015A, Ch 47, Fig 17]

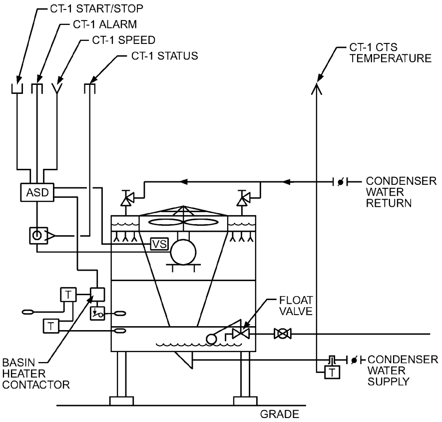


Figure 20.6 Cooling Tower [2015A, Ch 47, Fig 13]

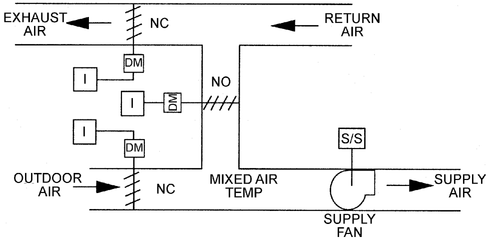


Figure 20.7 Economizer Cycle Control

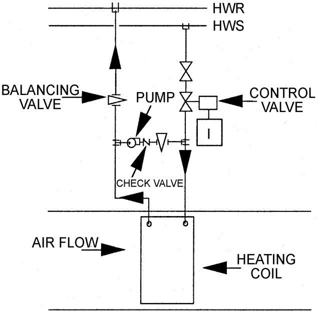


Figure 20.8 Preheat with Secondary Pump and Two-Way Valve

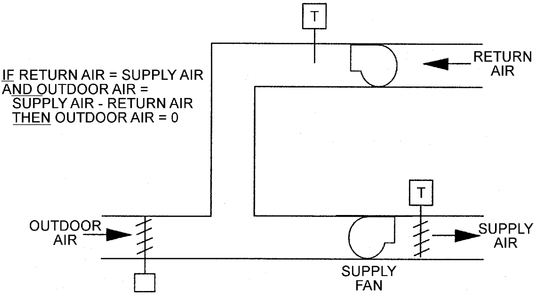


Figure 20.9 Warm-Up Control

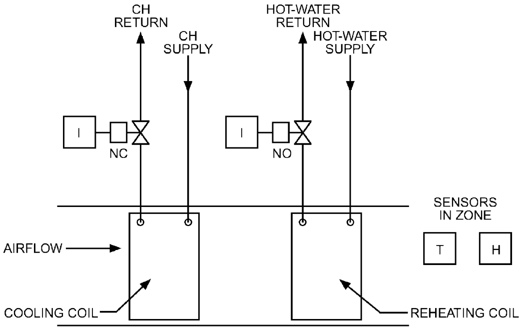


Figure 20.10 Cooling and Dehumidifying with Reheat [2015A, Ch 47, Fig 32]

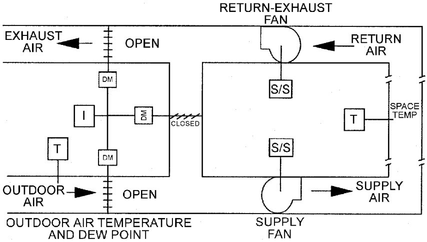


Figure 20.11 Night Cooldown Control

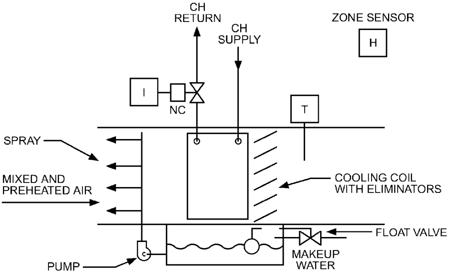


Figure 20.12 Sprayed Coil Dehumidifier [2015A, Ch 47, Fig 33]

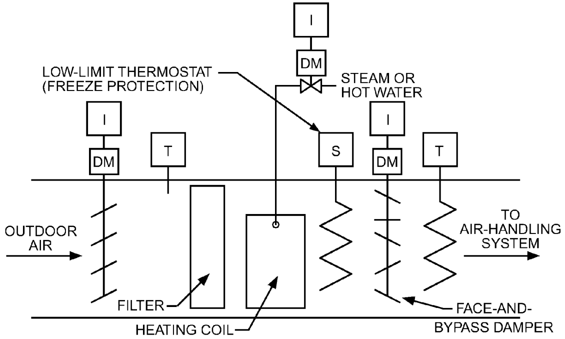


Figure 20.13 Preheat with Face and Bypass Dampers [2015A, Ch 47, Fig 5]

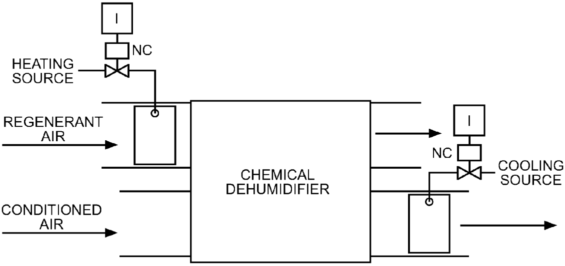


Figure 20.14 Chemical Dehumidifier [2015A, Ch 47, Fig 35]

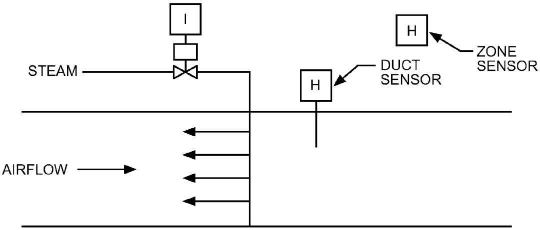


Figure 20.15 Steam Jet Humidifier [2015A, Ch 47, Fig 36]

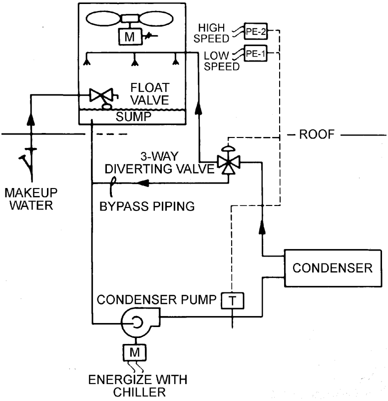


Figure 20.16 Condenser Water Temperature Control

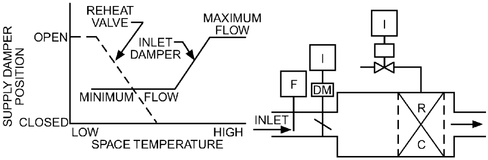


Figure 20.17 Throttling VAV Terminal Unit [2015A, Ch 47, Fig 25]

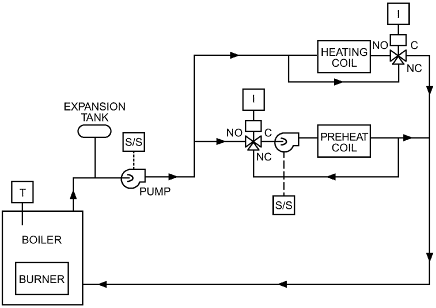


Figure 20.18 Load and Zone Control in Simple Hydronic System [2015A, Ch 47, Fig 3]

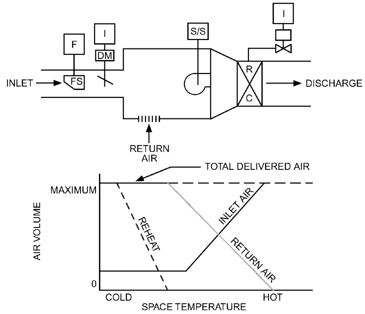


Figure 20.19 Fan-Powered VAV Terminal Unit [2015A, Ch 47, Fig 28]

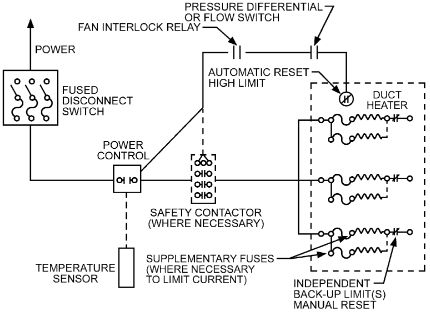


Figure 20.20 Duct Heater Control [2015A, Ch 47, Fig 9]

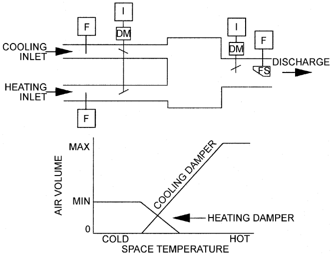


Figure 20.21 Pressure-Independent Dual-Duct VAV Terminal Unit

Automatic Controls

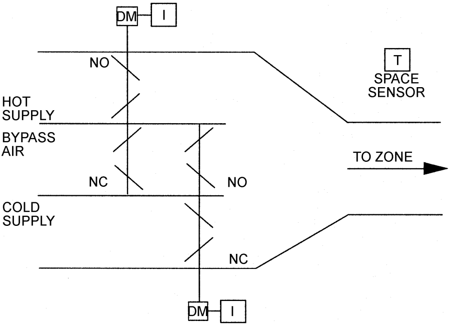


Figure 20.22 Zone Mixing Dampers—Three-Deck Multizone System

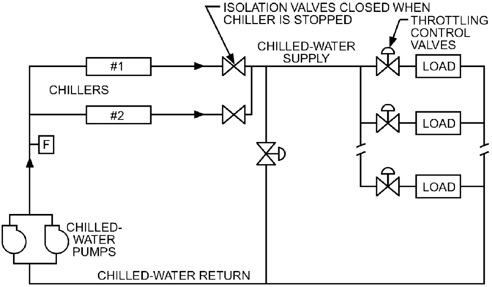


Figure 20.23 Variable-Flow Chilled-Water System (Primary Only) [2015A, Ch 47, Fig 10]

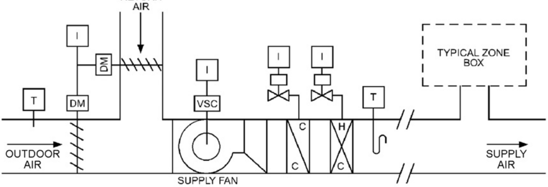


Figure 20.24 Multizone Single-Duct System [2015A, Ch 47, Fig 42]

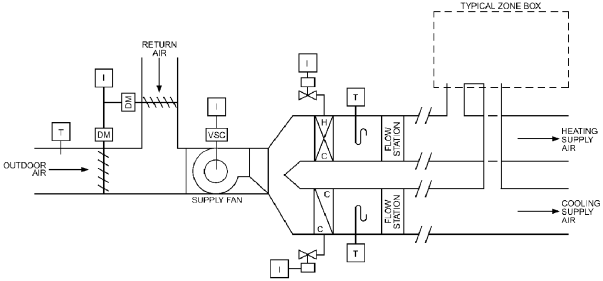


Figure 20.25 Dual-Duct Single Supply Fan System [2015A, Ch 47, Fig 43]

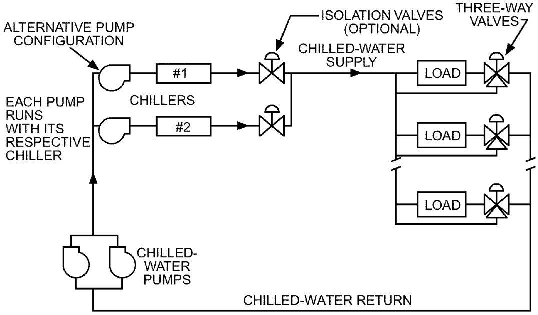
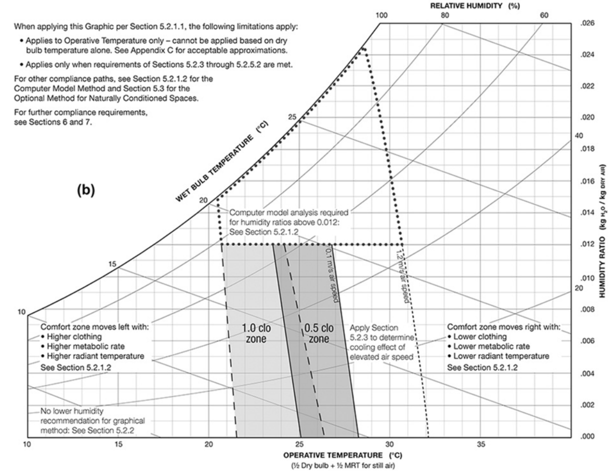


Figure 20.26 Constant-Flow Chilled-Water System (Primary/Only) [2015A, Ch 47, Fig 12]

21. OCCUPANT COMFORT

ASHRAE Standard 55-2013, *Thermal Environmental Conditions for Human Occupancy*

(*See complete standard for detailed guidance.*)



Acceptable ranges of operative temperature and humidity for people in 0.5 to 1.0 clo clothing, activity between 1.0 met and 1.3 met. The operative temperature ranges are based on a 80% satisfaction criterion; 10% general dissatisfaction and 10% partial (local) dissatisfaction.

Figure 21.1 Graphic Comfort Zone Method [Std 55-2013, Fig 5.3.1]

Table 21.1 Acceptable Thermal Environment for General Comfort
[Std 55-2013, Tbl F3]

PPD	PMV Range
< 10	–0.5 < PMV < + 0.5

temperature, operative **(t_o):** the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment. An acceptable approximation that operative temperature equals air temperature exists when there is no radiant or radiant panel heating or cooling system; there is no major heat generating equipment in the space; the wall/window $U_w < 50/(t_{di} - t_{de})$, where t_{di} is the inside design temperature and t_{de} is the outside design temperature; and window solar heat gain coefficient (SHGC) < 0.48. Where air speed is low and t_{air} is closer than 4 K to $t_{mean\ radiant}$, the t_{op} is their mean value.

A computer program is presented in Appendix B of Standard 55-2013 to calculate predicted mean vote (PMV). The PPD (predicted percentage of people dissatisfied) is a function of the PMV.

Table 21.2 Typical Insulation and Permeation Efficiency Values for Western Clothing Ensembles [2017F, Ch 9, Tbl 7]

Ensemble Description[a]	I_{cl}, clo	I_t,[b] clo	f_{cl}	i_{cl}	i_m[b]
Walking shorts, short-sleeved shirt	0.36	1.02	1.10	0.34	0.42
Trousers, short-sleeved shirt	0.57	1.20	1.15	0.36	0.43
Trousers, long-sleeved shirt	0.61	1.21	1.20	0.41	0.45
Same as above, plus suit jacket	0.96	1.54	1.23		
Same as above, plus vest and T-shirt	1.14	1.69	1.32	0.32	0.37
Trousers, long-sleeved shirt, long-sleeved sweater, T-shirt	1.01	1.56	1.28		
Same as above, plus suit jacket and long underwear bottoms	1.30	1.83	1.33		
Sweat pants, sweat shirt	0.74	1.35	1.19	0.41	0.45
Long-sleeved pajama top, long pajama trousers, short 3/4 sleeved robe, slippers (no socks)	0.96	1.50	1.32	0.37	0.41
Knee-length skirt, short-sleeved shirt, panty hose, sandals	0.54	1.10	1.26		
Knee-length skirt, long-sleeved shirt, full slip, panty hose	0.67	1.22	1.29		
Knee-length skirt, long-sleeved shirt, half slip, panty hose, long-sleeved sweater	1.10	1.59	1.46		
Same as above, replace sweater with suit jacket	1.04	1.60	1.30	0.35	0.40
Ankle-length skirt, long-sleeved shirt, suit jacket, panty hose	1.10	1.59	1.46		
Long-sleeved coveralls, T-shirt	0.72	1.30	1.23		
Overalls, long-sleeved shirt, T-shirt	0.89	1.46	1.27	0.35	0.40
Insulated coveralls, long-sleeved thermal underwear, long underwear bottoms	1.37	1.94	1.26	0.35	0.39

Sources: McCullough and Jones (1984) and McCullough et al. (1989).

[a] All ensembles include shoes and briefs or panties. All ensembles except those with panty hose include socks unless otherwise noted.

[b] For $t_r = t_a$ and air velocity less than 40 fpm (I_a = 0.72 clo and i_m = 0.48 when nude).

Table 21.3 Insulation and Permeability Values for a Selection of Non-Western Clothing Ensembles [2017F, Ch 9, Tbl 8]

Ensemble Description[a]	Country	I_{cl} clo	I_t, clo	f_{cl}	i_m
Shalwar (pants), kameez (shirt), scarf, sandals (f)	Pakistan	0.69	1.1	1.41	0.32
Shalwar (pants), kameez (shirt), socks, athletic shoes (m)	Pakistan	0.86	1.3	1.36	0.35
Dishdasha (thowb or caftan), short-sleeved t-shirt, long serwal (pants), tagiya (hat), iqal (cord), ghutra (headdress), socks, athletic shoes (m)	Kuwait	1.36	1.7	1.66	0.30
Full slip, double-layer abaya (dress), anta (head cover), hijab (headscarf), sandals (f)	Kuwait	1.27	1.7	1.65	0.33
Underskirt, blouse, sari, sandals (f)	India	0.74	1.2	1.46	0.33
Churidhar pants, churidhar dress, shawl, sandals (f)	India	0.58	1.1	1.28	0.36
Short shirt with long sleeves, long pants, boubou (wide-sleeved robe), kufi (hat), sandals (m)	Nigeria/ Ghana	1.40	1.7	1.96	0.42
Short shirt with long sleeves, long pants, sandals (f)	Nigeria/ Ghana	0.78	1.3	1.35	0.40
Long-sleeved shirt, skirt, headscarf, socks, athletic shoes (f)	Indonesia	0.97	1.4	1.43	0.31
Camisole, short-sleeved qipao (dress), sandals (f)	China	0.42	0.9	1.31	0.40

(f) = clothing traditionally worn by women
(m) = clothing traditionally worn by men
Source: Havenith et al. (2015). Values are the means of manikin-based measurements conducted in three laboratories. All ensembles include bra and panties (female) and briefs (male). For all women's ensembles, I_a = 0.64 clo; for all men's ensembles, I_a = 0.63 clo.

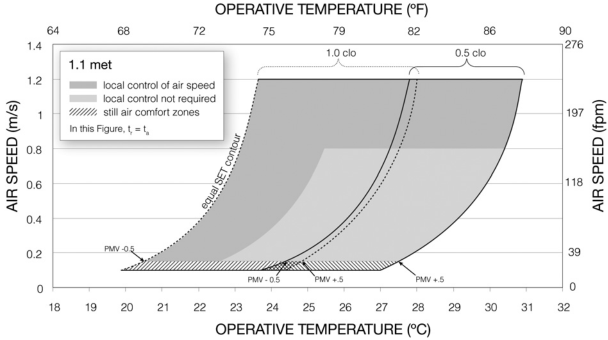


Figure 21.2 Acceptable Range of Operative Temperature and Air Speeds for the Comfort Zone Shown in Figure 21.1, at Humidity Ratio 0.010 [Std 55-2013, Fig 5.3.3A]

Table 21.4 Percentage Dissatisfied Due to Local Discomfort from Draft (DR) or Other Sources (PD) [Std 55-2013, Tbl H1]

DR Due to Draft	PD Due to Vertical Air Temperature Difference	PD Due to Warm or Cool Floors	PD Due to Radiant Asymmetry
< 20%	< 5%	< 10%	< 5%

Table 21.5 Allowable Radiant Temperature Asymmetry [Std 55-2013, Tbl 5.3.4.2]

Radiant Temperature Asymmetry °C			
Warm Ceiling	**Cool Wall**	**Cool Ceiling**	**Warm Wall**
< 5	< 10	< 14	< 23

Table 21.6 Limits on Temperature Drifts and Ramps [Std 55-2013, Tbl 5.3.5.3]

Time Period	0.25 h	0.5 h	1 h	2 h	4 h
Maximum Operative Temperature Change Allowed	1.1°C	1.7°C	2.2°C	2.8°C	3.3°C

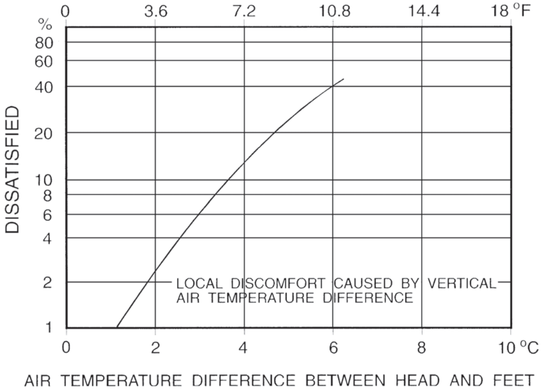


Figure 21.3 Local Thermal Discomfort caused by Vertical Temperature Differences
[Std 55-2013, Fig H4]

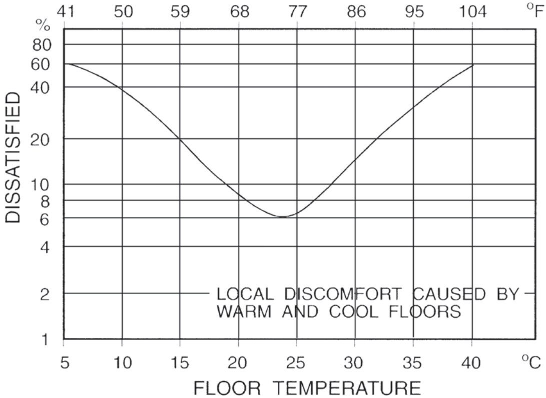


Figure 21.4 Local Discomfort caused by Warm and Cool Floors [Std 55-2013, Fig H5]

Table 21.7 Increases in Acceptable Operative Temperature Limits (Δt_0) in Occupant-Controlled, Naturally Conditioned Spaces (Figure 21.6) Resulting from Increasing Air Speed above 0.3 m/s [Std 55-2013, Tbl 5.4.2.4]

Average Air Speed (V_a) 0.6 m/s	Average Air Speed (V_a) 0.9 m/s	Average Air Speed (V_a) 1.2 m/s
1.2°C	1.8°C	2.2°C

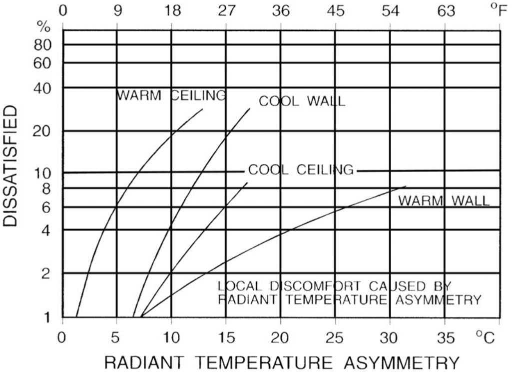


Figure 21.5 Local Thermal Discomfort caused by Radiant Asymmetry [Std 55-2013, Fig H2]

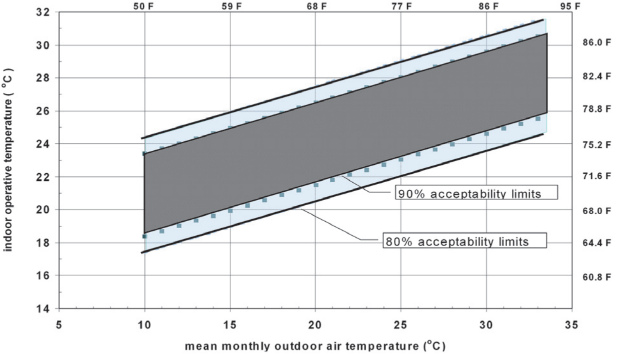


Figure 21.6 Thermal Comfort in Naturally Ventilated Buildings [Std 55-2013, Fig 5.4.2]

Use Figure 21.6 to calculate the average of the mean minimum and maximum air temperatures for a given month, and then use the chart to determine the acceptable range of indoor operative temperatures for a naturally ventilated building. During the design phase of a building, these numbers could be compared to the output of a thermal simulation model of the proposed building to determine whether the predicted indoor temperatures are likely to be comfortable using natural ventilation, or if air conditioning would be required. Figure 21.6 also could be used to evaluate the acceptability of thermal conditions in an existing building by comparing the acceptable temperature range obtained from the chart to indoor temperatures measured in the building.

Figure 21.6 is applicable where occupants control operable windows, where activity levels are between 1.0 and 1.3 met, and where occupants may freely adapt their clothing to the indoor and/or outdoor thermal conditions.

22. GENERAL

Table 22.1 General Design Criteria[a, b] [2007A, Ch 3, Tbl 1]

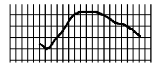
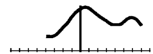
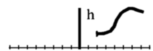
General Category	Specific Category	Inside Design Conditions: Winter	Inside Design Conditions: Summer	Air Movement	Circulation, ach	Noise[c]	Filtering Efficiencies (ASHRAE Std. 52.1)	Load Profile	Comments
Dining and Entertainment Centers	Cafeterias and Luncheonettes	21 to 23°C 20 to 30% rh	26°C[d] 50% rh	0.25 m/s at 1.8 m above floor	12 to 15	NC 40 to 50[e]	35% or better	Peak at 1 to 2 PM 	Prevent draft discomfort for patrons waiting in serving lines
	Restaurants	21 to 23°C 20 to 30% rh	23 to 26°C 55 to 60% rh	0.13 to 0.15 m/s	8 to 12	NC 35 to 40	35% or better	Peak at 1 to 2 PM 	
	Bars	21 to 23°C 20 to 30% rh	23 to 26°C 50 to 60% rh	0.15 m/s at 1.8 m above floor	15 to 20	NC 35 to 50	Use charcoal for odor control with manual purge control for 100% outside air to exhaust ±35% prefilters	Peak at 5 to 7 PM 	
	Nightclubs and Casinos	21 to 23°C 20 to 30% rh	23 to 26°C 50 to 60% rh	below 0.13 m/s at 1.5 m above floor	20 to 30	NC 35 to 45[f]	Use charcoal for odor control with manual purge control for 100% outside air to exhaust ±35% prefilters	Nightclubs peak at 8 PM to 2 AM; Casinos peak at 4 PM to 2 AM; Equipment, 24 h/day	Provide good air movement but prevent cold draft discomfort for patrons
	Kitchens	21 to 23°C	29 to 31°C	0.15 to 0.25 m/s	12 to 15[g]	NC 40 to 50	10 to 15% or better		Negative air pressure required for odor control (also see 2015A, Ch 33)

Table 22.1 General Design Criteria[a, b] [2007A, Ch 3, Tbl 1] (*Continued*)

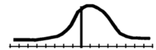
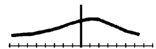
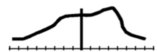
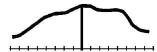
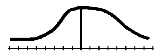
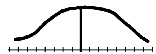
General Category	Specific Category	Inside Design Conditions: Winter	Inside Design Conditions: Summer	Air Movement	Circulation, ach	Noise[c]	Filtering Efficiencies (ASHRAE Std. 52.1)	Load Profile	Comments
Office Buildings		21 to 23°C 20 to 30% rh	23 to 26°C 50 to 60% rh	0.13 to 0.23 m/s 4 to 10 L/(s·m^2)	4 to 10	NC 30 to 40	35 to 60% or better	Peak at 4 PM 	
Museums, Galleries, Libraries and Archives	Average	20 to 22°C 40 to 55% rh		below 0.13 m/s	8 to 12	NC 35 to 40	35 to 60% or better	Peak at 3 PM 	
	Archival	See 2015A, Ch 23		below 0.13 m/s	8 to 12	NC 35	35% prefilters plus charcoal filters 85 to 95% final[i]	Peak at 3 PM 	
Bowling Centers		21 to 23°C 20 to 30% rh	24 to 26°C 50 to 55% rh	0.25 m/s at 1.8 m above floor	10 to 15	NC 40 to 50	10 to 15%	Peak at 6 to 8 PM 	
Communication Centers	Telephone Terminal Rooms	22 to 26°C 40 to 50% rh	22 to 26°C 40 to 50% rh	0.13 to 0.15 m/s	8 to 20	to NC 60	85% or better	Varies with location and use	Constant temperature and humidity required
	Radio and Television Studios	21 to 23°C 40 to 50% rh	23 to 26°C 45 to 55% rh	0.13 to 0.15 m/s	15 to 40	NC 15 to 25	35% or better	Varies widely because of changes in lighting and people	Constant temperature and humidity required

Table 22.1 General Design Criteria[a, b] [2007A, Ch 3, Tbl 1] (*Continued*)

General Category	Specific Category	Inside Design Conditions: Winter	Inside Design Conditions: Summer	Air Movement	Circulation, ach	Noise[c]	Filtering Efficiencies (ASHRAE Std. 52.1)	Load Profile	Comments
Transportation Centers (also see 2015A, Ch 15)	Airport Terminals	23 to 26°C 30 to 40% rh	23 to 26°C 40 to 55% rh	below 0.13 m/s at 3.7 m above floor	8 to 12	NC 35 to 50	35% or better and charcoal filters	Peak at 10 AM to 9 PM 	Positive air pressure required in terminal
	Ship Docks	21 to 23°C 20 to 30% rh	23 to 26°C 50 to 60% rh	0.13 to 0.15 m/s at 1.8 m above floor	8 to 12	NC 35 to 50	10 to 15%	Peak at 10 AM to 5 PM 	Positive air pressure required in waiting area
	Bus Terminals	21 to 23°C 20 to 30% rh	23 to 26°C 50 to 60% rh	0.13 to 0.15 m/s at 1.8 m above floor	8 to 12	NC 35 to 50	35% with exfiltration	Peak at 10 AM to 5 PM 	Positive air pressure required in terminal
	Garages[j]	4 to 13°C	27 to 38°C	0.15 to 0.38 m/s	4 to 6	NC 35 to 50	10 to 15%	Peak at 10 AM to 5 PM 	Negative air pressure required to remove fumes; positive air in pressure adjacent occupied spaces
Warehouses		Inside design temperatures for warehouses often depend on the materials stored.			1 to 4	to NC 75	10 to 35%	Peak at 10 AM to 3 PM 	

Notes to General Design Criteria

[a]This table shows design criteria differences between various commercial and public buildings. It should not be used as sole source for design criteria. Each type of data contained here can be determined from *ASHRAE Handbook* and standards.

[b]Consult governing codes to determine minimum allowable requirements. Outside air requirements may be reduced if high-efficiency adsorption equipment or other odor- or gas-removal equipment is used. See ASHRAE Standard 62.1 for calculation procedures.

[c]Refer to Chapter 48 of the 2011 *ASHRAE Handbook—HVAC Applications*.

[d]Food in these areas is often eaten more quickly than in a restaurant; therefore, turnover of diners is much faster. Because diners seldom remain for long periods, they do not require the degree of comfort necessary in restaurants. Thus, it may be possible to lower design criteria standards and still provide reasonably comfortable conditions. Although space conditions of 27°C and 50% rh may be satisfactory for patrons when it is 35°C and 50% rh outside, inside conditions of 26°C and 40% rh are better.

[e]Cafeterias and luncheonettes usually have some or all food preparation equipment and trays in the same room with diners. These establishments are generally noisier than restaurants, so noise transmission from air-conditioning equipment is not as critical.

[f]In some nightclubs, air-conditioning system noise must be kept low so patrons can hear the entertainment.

[g]Usually determined by kitchen hood requirements.

[h]Peak kitchen heat load does not generally occur at peak dining load, although in luncheonettes and some cafeterias where cooking is done in dining areas, peaks may be simultaneous.

[i]Methods for removing chemical pollutants must also be considered.

[j]Also includes service stations.

SI Units and Air-Conditioning Formulas

length = metre, m

mass = kilogram, kg

time = second, s

electric current = ampere, A

thermodynamic temperature = K

temperature, celsius (°C) = (K – 273)

amount of substance = mole, mol

energy enthalpy, work = Joule, J

heat, watts = W (J/s)

power, watts = W (J/s)

force, newton = N (kg · m^2)

pressure, pascal = Pa (N/m^2) (head, 1 m = 9.81 kPa)

Prefixes:

giga, G= 10^9	nano, n = 10^{-9}
mega, M = 10^6	micro, μ = 10^{-6}
kilo, k = 10^3	milli, m = 10^{-3}

density	water 100 kg/m^3,	air 1.2 kg/m^3
specific heat	water 4.2 kJ/kg·K,	air 1.009 kJ/kg·K

Air-Conditioning Formulas:

Sensible heat, SH = 1.2 Q Δt

Total heat, TH = 1.2 Q Δh

Latent heat, LH = 3.0 Q ΔW

where heat is in W:

Δt = temperature difference, K or °C

Δh = enthalpy difference, kJ/kg

ΔW = moisture concentration difference, g/kg dry air

Q = flow rate of air, L/s

Pump Power

$$P = Q \times h \times \rho / nC_w$$

where

P = kW,

Q = L/s flow rate

h = kPa head

ρ = density ratio to water

n = efficiency, 50% to 85% usually

C_w = constant, 101

Fan Power

$$P = Q \times h \times \rho / nC_a$$

P = kW,

Q = L/s flow rate

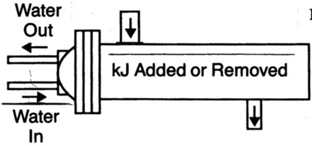
h = kPa head

ρ = density ratio to air

n = efficiency, 40% to 70% usually

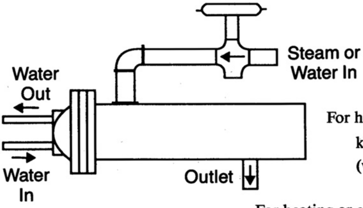
C_a = constant, 40350

Sizing Formulas



For heating or cooling water:

$$L/s = \frac{0.24 \text{ kW}}{(\text{water temp. rise or drop, °C})}$$

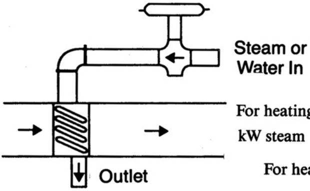


For heating water with steam:

$$\text{kW steam} = 4.187 \text{ L/s}$$
$$(\text{water temp. rise, °C})$$

For heating or cooling water with water:

$$(L/s)_1 = (L/s)_2 \left(\frac{\text{water}_2 \text{ temp. rise or drop, °C}}{\text{water}_1 \text{ temp. rise or drop, °C}}\right)$$



For heating air with steam coils:

$$\text{kW steam} = 0.012\,(L/s)\,(\text{air temp. rise, °C})$$

For heating air with water coils:

$$(L/s)_{water} = (1/3450)\,(L/s)_{air} \left(\frac{\text{air temp. rise, °C}}{\text{water temp. drop, °C}}\right)$$

Figure 22.1 Sizing Formulas for Heating/Cooling

Table 22.2 Conversions to I-P and SI Units [2017F, Ch 38, Tbl 1]
(Multiply I-P values by conversion factors to obtain SI; divide SI values by conversion factors to obtain I-P)

Multiply I-P	By	To Obtain SI
acre (43 560 ft^2)	0.4047	ha
	4046.873	m^2
atmosphere (standard)	*101.325	kPa
bar	*100	kPa
barrel (42 U.S. gal, petroleum)	159.0	L
	0.1580987	m^3
Btu (International Table)	1055.056	J
Btu (thermochemical)	1054.350	J
Btu/ft^2 (International Table)	11,356.53	J/m^2
Btu/ft^3 (International Table)	37,258.951	J/m^3
Btu/gal	278,717.1765	J/m^3
Btu·ft/h·ft^2·°F	1.730735	W/(m·K)
Btu·in/h·ft^2·°F (thermal conductivity k).	0.1442279	W/(m·K)
Btu/h	0.2930711	W
Btu/h·ft^2	3.154591	W/m^2
Btu/h·ft^2·°F (overall heat transfer coefficient U)	5.678263	W/(m^2·K)
Btu/lb	*2.326	kJ/kg
Btu/lb·°F (specific heat c_p)	*4.1868	kJ/(kg·K)
bushel (dry, U.S.)	0.0352394	m^3
calorie (thermochemical)	*4.184	J
centipoise (dynamic viscosity μ)	*1.00	mPa·s
centistokes (kinematic viscosity ν)	*1.00	mm^2/s
clo	0.155	(m^2·K)/W
dyne	1.0×10^{-5}	N
dyne/cm^2	*0.100	Pa
EDR hot water (150 Btu/h)	43.9606	W
EDR steam (240 Btu/h)	70.33706	W
EER	0.293	COP
ft	*0.3048	m
	*304.8	mm
ft/min, fpm	*0.00508	m/s
ft/s, fps	*0.3048	m/s
ft of water	2989	Pa
ft of water per 100 ft pipe	98.1	Pa/m
ft^2	0.092903	m^2
ft^2·h·°F/Btu (thermal resistance R)	0.176110	(m^2·K)/W
ft^2/s (kinematic viscosity ν)	92,900	mm^2/s
ft^3	28.316846	L
	0.02832	m^3
ft^3/min, cfm	0.471947	L/s
ft^3/s, cfs	28.316845	L/s
ft·lb_f (torque or moment)	1.355818	N·m
ft·lb_f (work)	1.356	J
ft·lb_f/lb (specific energy)	2.99	J/kg
ft·lb_f/min (power)	0.0226	W
footcandle	10.76391	lx
gallon (U.S., *231 in^3)	3.785412	L
gph	1.05	mL/s
gpm	0.0631	L/s
gpm/ft^2	0.6791	L/(s·m^2)
gpm/ton refrigeration	0.0179	mL/J
grain (1/7000 lb)	0.0648	g
gr/gal	17.1	g/m^3
gr/lb	0.143	g/kg
horsepower (boiler) (33 470 Btu/h)	9.81	kW
horsepower (550 ft·lb_f/s)	0.7457	kW
inch	*25.4	mm
in. of mercury (60°F)	3.3864	kPa
in. of water (60°F)	248.84	Pa
in/100 ft, thermal expansion coefficient	0.833	mm/m

Table 22.2 Conversions to I-P and SI Units [2017F, Ch 38, Tbl 1] **(*Continued*)**
(Multiply I-P values by conversion factors to obtain SI; divide SI values by conversion factors to obtain I-P)

Multiply I-P	By	To Obtain SI
in·lb_f (torque or moment)	113	mN·m
in^2	645.16	mm^2
in^3 (volume)	16.3874	mL
in^3/min (SCIM)	0.273117	mL/s
in^3 (section modulus)	16,387	mm^3
in^4 (section moment)	416, 231	mm^4
kWh	*3.60	MJ
kW/1000 cfm	2.118880	kJ/m^3
kilopond (kg force)	9.81	N
kip (1000 lb_f)	4.45	kN
kip/in^2 (ksi)	6.895	MPa
litre	*0.001	m^3
met	58.15	W/m^2
micron (μm) of mercury (60°F)	133	mPa
mile	1.609	km
mile, nautical	*1.852	km
mile per hour (mph)	1.609344	km/h
	0.447	m/s
millibar	*0.100	kPa
mm of mercury (60°F)	0.133	kPa
mm of water (60°F)	9.80	Pa
ounce (mass, avoirdupois)	28.35	g
ounce (force or thrust)	0.278	N
ounce (liquid, U.S.)	29.6	mL
ounce inch (torque, moment)	7.06	mN·m
ounce (avoirdupois) per gallon	7.489152	kg/m^3
perm (permeance at 32°F)	5.72135×10^{-11}	kg/(Pa·s·m^2)
perm inch (permeability at 32°F)	1.45362×10^{-12}	kg/(Pa·s·m)
pint (liquid, U.S.)	4.73176×10^{-4}	m^3
pound		
lb (avoirdupois, mass)	0.453592	kg
	453.592	g
lb_f (force or thrust)	4.448222	N
lb_f/ft (uniform load)	14.59390	N/m
lb/ft·h (dynamic viscosity μ)	0.4134	mPa·s
lb/ft·s (dynamic viscosity μ)	1490	mPa·s
lb_f·s/ft^2 (dynamic viscosity μ)	47.88026	Pa·s
lb/h	0.000126	kg/s
lb/min	0.007559	kg/s
lb/h [steam at 212°F (100°C)]	0.2843	kW
lb_f/ft^2	47.9	Pa
lb/ft^2	4.88	kg/m^2
lb/ft^3 (density ρ)	16.0	kg/m^3
lb/gallon	120	kg/m^3
ppm (by mass)	*1.00	mg/kg
psi	6.895	kPa
quad (10^{15} Btu)	1.055	EJ
quart (liquid, U.S.)	0.9463	L
square (100 ft^2)	9.2903	m^2
tablespoon (approximately)	15	mL
teaspoon (approximately)	5	mL
therm (U.S.)	105.5	MJ
ton, long (2240 lb)	1.016046	Mg
ton, short (2000 lb)	0.907184	Mg; t (tonne)
ton, refrigeration (12 000 Btu/h)	3.517	kW
torr (1 mm Hg at 0°C)	133	Pa
watt per square foot	10.76	W/m^2
yd	*0.9144	m
yd^2	0.8361	m^2
yd^3	0.7646	m^3

*Conversion factor is exact.

Notes: 1. Units are U.S. values unless noted otherwise.

2. Litre is a special name for the cubic decimetre. 1 L = 1 dm^3 and 1 mL = 1 cm^3.

General

23. APPENDIX

DB: Dry-bulb temperature, °C *WB: Wet-bulb temperature, °C* *DP: Dew-point temperature, °C*
MCWB: Mean coincident wet-bulb temperature, °C *HDD and CDD 18.3: Annual heating and cooling degree-days, base 18.3°C, °C-day*

Appendix: Climatic Design Conditions for Selected Locations

Station	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
United States of America										
Alabama										
AUBURN UNIVERSITY REGIONAL	–4.9	–2.5	34.1	23.0	32.9	23.3	32.3	23.1	1342	1064
BIRMINGHAM SHUTTLESWORTH INTL	–6.2	–3.9	35.4	23.7	34.0	23.6	32.8	23.5	1450	1141
CAIRNS AAF	–2.9	–1.2	35.3	24.6	34.1	24.5	33.0	24.2	998	1321
DOTHAN REGIONAL	–2.6	–0.6	35.8	24.3	34.4	24.1	33.3	23.9	964	1401
HUNTSVILLE INTL	–7.4	–5.1	35.2	23.9	33.8	23.7	32.6	23.4	1696	1026
MAXWELL AFB	–3.5	–1.3	36.4	24.5	35.3	24.6	34.1	24.6	1087	1414
MOBILE REGIONAL	–2.4	–0.5	34.5	24.9	33.5	24.7	32.5	24.5	912	1398
MONTGOMERY REGIONAL	–4.3	–2.3	36.0	24.5	34.8	24.4	33.7	24.2	1172	1307
NORTHEAST ALABAMA AP	–7.3	–5.2	34.1	23.6	32.9	23.6	32.2	23.5	1766	883
NORTHWEST ALABAMA REGIONAL	–6.8	–4.5	35.7	24.1	34.3	24.0	33.0	23.7	1665	1059
TUSCALOOSA REGIONAL	–5.3	–3.0	36.3	24.1	34.8	24.3	33.6	24.1	1361	1222
Alaska										
BRYANT AAF	–28.7	–25.5	23.8	15.7	22.0	14.9	20.1	13.9	5932	3
ELMENDORF AFB	–26.3	–23.7	23.4	14.8	22.0	14.3	20.1	13.5	5736	7
FAIRBANKS INTL	–41.6	–39.2	27.4	16.0	25.6	15.5	23.8	14.7	7543	38
JUNEAU INTL	–15.2	–12.8	23.3	15.3	21.2	14.5	19.2	13.6	4654	2
LAKE HOOD SEAPLANE BASE	–22.3	–19.8	23.3	15.3	21.5	14.5	19.9	13.7	5412	8
MERRILL FIELD	–23.7	–21.7	22.9	15.2	21.4	14.6	20.0	13.9	5534	7
TED STEVENS ANCHORAGE INTL	–22.6	–20.3	21.9	15.0	20.2	14.1	18.9	13.5	5619	3
Arizona										
CASA GRANDE MUNICIPAL	–0.1	1.6	42.5	20.9	41.4	20.6	40.3	20.3	832	1986
DAVIS-MONTHAN AFB	0.2	1.9	40.7	18.4	39.3	18.3	38.0	18.1	809	1790

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
FLAGSTAFF PULLIAM AP	–15.6	–12.6	29.9	12.9	28.6	12.7	27.4	12.6	3778	72
LUKE AFB	1.6	3.0	43.8	21.1	42.6	21.0	41.4	20.9	679	2245
PHOENIX SKY HARBOR INTL	4.0	5.4	43.5	20.8	42.4	20.7	41.3	20.6	507	2576
PRESCOTT MUNICIPAL	–7.9	–6.2	34.7	15.9	33.4	15.6	32.3	15.4	2303	567
TUCSON INTL	–0.1	1.4	41.0	18.9	39.8	18.7	38.6	18.5	778	1839
WINDOW ROCK AP	–17.7	–14.9	32.1	13.4	31.0	13.2	29.5	12.8	3553	170
YUMA INTL AP	5.7	7.1	43.9	22.5	42.7	22.4	41.9	22.0	365	2638
Arkansas										
BENTONVILLE MUNICIPAL	–12.2	–8.9	35.9	23.6	33.6	23.6	32.4	23.4	2246	798
CLINTON NATL	–6.3	–4.2	37.1	25.0	35.6	25.0	34.1	24.8	1609	1226
DRAKE FIELD	–12.0	–8.7	35.5	23.5	33.8	23.5	32.4	23.5	2201	792
FORT SMITH REGIONAL	–7.9	–5.4	37.9	24.3	36.3	24.5	34.7	24.4	1734	1184
GRIDER FIELD	–5.3	–3.4	36.4	25.3	35.1	25.1	33.9	24.9	1525	1235
JONESBORO MUNICIPAL	–8.3	–6.3	36.2	24.9	34.8	24.6	33.6	24.3	1947	1088
LITTLE ROCK AFB	–7.7	–5.4	37.7	25.1	36.1	25.3	34.6	25.1	1742	1166
NORTH LITTLE ROCK MUNICIPAL	–7.6	–4.9	35.2	24.8	33.9	24.6	32.7	24.2	1764	1076
ROGERS MUNICIPAL	–12.3	–9.1	35.0	22.9	33.3	23.1	32.1	22.9	2248	794
SMITH FIELD	–12.1	–8.8	36.2	23.5	34.0	23.5	32.5	23.4	2197	827
TEXARKANA REGIONAL	–4.6	–2.7	37.4	24.3	36.0	24.4	34.6	24.3	1360	1316
California										
ALAMEDA	40.4	42.4	81.1	64.0	77.2	62.9	73.9	62.0	2508	160
BEALE AFB	31.1	33.9	101.1	70.3	98.2	69.1	95.2	67.9	2398	1548
BOB HOPE AP	38.8	41.1	97.6	67.9	94.1	66.8	91.1	66.4	1381	1449
BROWN FIELD MUNICIPAL	39.0	41.5	89.5	64.1	85.2	64.6	82.0	64.6	1647	667
CAMARILLO AP	37.5	39.7	86.2	62.2	82.4	63.1	79.9	63.1	1819	421
CAMP PENDLETON MCAS	31.9	34.7	92.0	65.8	87.9	65.3	84.3	65.2	1818	679

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
CASTLE AFB	4.7	5.8	27.3	17.8	25.1	17.2	23.3	16.6	1393	89
DESERT RESORTS REGIONAL	–0.5	1.1	38.4	21.3	36.8	20.6	35.1	19.9	1332	860
EL TORO MCAS	3.8	5.0	36.4	19.9	34.5	19.3	32.8	19.1	767	805
FRESNO YOSEMITE INTL	3.9	5.3	32.0	17.8	29.5	18.1	27.8	18.1	915	371
FULLERTON MUNICIPAL	3.0	4.3	30.1	16.8	28.0	17.3	26.6	17.3	1011	234
HAWTHORN MUNICIPAL	0.0	1.5	33.3	18.8	31.1	18.5	29.0	18.4	1010	377
HAYWARD EXECUTIVE	–1.1	–0.1	39.2	20.9	37.7	20.1	36.5	19.6	1324	979
IMPERIAL COUNTY AP	–0.5	1.3	44.2	22.3	42.8	22.0	41.7	21.8	607	2175
LEMOORE NAS	6.2	7.4	33.3	19.9	31.6	19.7	30.0	19.3	617	651
LIVERMORE MUNICIPAL	–0.1	1.2	39.8	21.3	38.3	20.5	36.9	20.0	1231	1203
LOMPOC AP	4.3	6.0	35.0	19.4	32.9	19.3	31.3	19.0	618	751
LONG BEACH AP	6.9	7.7	31.1	17.1	28.9	17.2	27.3	17.5	614	455
LOS ANGELES INTL	7.1	8.2	28.8	17.3	26.9	17.7	25.4	17.9	715	341
LOS ANGELES ONTARIO INTL	3.6	4.8	37.9	21.0	36.4	20.2	34.8	19.9	767	998
MARCH AFB	0.1	1.7	38.5	19.9	37.1	19.4	35.5	19.0	1053	880
MCCLELLAN-PALOMAR AP	6.1	7.1	28.8	16.7	27.1	17.7	25.5	17.8	902	298
MEADOWS FIELD	0.3	1.9	39.4	21.3	38.0	20.7	36.7	20.1	1139	1288
MINETA SAN JOSE INTL	1.9	3.2	33.0	18.9	31.0	18.5	28.9	18.0	1191	347
MIRAMAR MCAS	3.9	5.2	32.6	18.8	30.8	18.8	28.9	18.6	827	469
MODESTO CITY-COUNTY AP	–0.7	0.7	38.5	21.0	36.8	20.2	35.2	19.5	1312	906
MOFFETT FEDERAL AIRFIELD	2.2	3.6	31.2	18.6	28.7	18.1	27.0	17.8	1217	259
MONTEREY REGIONAL	2.6	3.8	25.9	15.5	23.1	15.1	21.7	14.9	1795	28
MONTGOMERY FIELD	4.8	6.1	32.4	18.6	30.3	18.3	28.5	18.3	814	474
NAPA COUNTY AP	–1.6	–0.1	32.8	18.8	30.3	18.2	28.0	17.7	1768	134
NORTH ISLAND NAS	7.1	7.9	29.2	17.8	27.4	18.4	26.0	18.8	621	435
OAKLAND INTL	2.5	3.8	28.6	17.9	26.2	17.2	23.9	16.8	1496	91

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
PALM SPRINGS INTL	5.1	6.4	44.1	21.5	42.9	21.3	42.0	21.1	421	2441
POINT ARGUELLO	7.6	8.6	22.0	N/A	20.0	N/A	18.6	N/A	1892	13
POINT MUGU NAS	3.8	5.0	27.5	16.2	25.8	16.9	24.1	17.2	1154	118
PORTERVILLE MUNICIPAL	–1.0	0.8	38.0	21.1	37.4	20.7	36.2	20.0	1400	947
REDDING MUNICIPAL	–2.0	–0.6	40.7	20.2	38.9	19.5	37.3	18.9	1501	1049
RIVERSIDE MUNICIPAL	2.5	3.7	37.9	20.7	36.5	20.2	34.9	19.7	804	954
SACRAMENTO EXECUTIVE	–0.6	0.9	37.8	21.0	36.0	20.2	34.2	19.6	1384	679
SACRAMENTO INTL	–0.9	0.7	38.0	21.3	36.4	20.7	34.8	20.0	1387	758
SACRAMENTO MATHER AP	–2.4	–1.1	38.5	20.4	36.8	19.7	34.9	19.2	1539	661
SACRAMENTO MCCLELLAN AFB	–1.0	0.6	39.0	21.1	37.4	20.4	35.5	19.7	1291	882
SALINAS MUNICIPAL	1.0	2.4	28.4	16.7	25.9	16.1	23.9	15.9	1504	62
SAN BERNARDINO INTL	1.1	2.5	39.4	20.9	37.9	20.8	36.3	20.4	918	1006
SAN DIEGO INTL	7.2	8.3	28.7	18.2	27.0	18.6	25.7	18.7	651	397
SAN FRANCISCO INTL	4.1	5.3	28.1	17.0	25.5	16.6	23.5	16.4	1488	87
SAN LUIS OBISPO CO REGIONAL	1.1	2.4	31.7	17.8	29.0	17.3	27.3	17.1	1235	163
SANTA BARBARA MUNICIPAL	1.6	2.8	28.3	17.4	26.5	17.6	25.0	17.3	1236	121
SANTA MARIA PUBLIC AP	0.7	2.0	29.0	16.6	26.7	16.3	24.8	16.0	1482	64
SONOMA COUNTY AP	–1.7	–0.5	34.8	19.1	32.7	18.7	30.7	18.0	1659	203
SOUTHERN CALIFORNIA LOGISTICS	–2.5	–0.9	38.2	18.5	36.9	18.2	35.6	17.7	1478	1062
STOCKTON METROPOLITAN	–1.0	0.4	38.4	21.1	36.6	20.5	34.9	20.0	1360	774
TRAVIS AFB	–1.1	0.6	37.2	19.8	35.0	19.2	32.9	18.7	1398	552
VISALIA MUNICIPAL	–1.2	0.2	37.8	22.1	37.1	21.6	35.9	21.1	1394	912
WILLIAM J FOX AP	–6.0	–4.0	39.4	18.8	37.9	18.0	36.7	17.5	1632	1050
Colorado										
BUCKLEY AFB	–17.5	–13.8	34.0	14.7	32.6	14.7	31.1	14.6	3221	382
CENTENNIAL AP	–17.8	–14.6	33.3	15.3	32.2	15.1	30.7	14.9	3362	349

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
COLORADO SPRINGS MUNICIPAL	–17.0	–13.9	32.7	14.8	31.3	14.7	29.8	14.6	3398	281
DENVER INTL	–18.2	–14.8	34.9	15.4	33.5	15.4	31.9	15.3	3297	451
DENVER STAPLETON	–18.6	–14.9	34.4	15.9	32.9	15.6	31.4	15.3	3148	401
FORT COLLINS DOWNTOWN	–19.2	–15.1	32.3	16.1	30.7	15.8	29.1	15.6	3387	257
FORT COLLINS LOVELAND MUNI	–17.9	–14.7	34.1	16.1	32.7	16.0	31.3	15.8	3442	347
GRAND JUNCTION REGIONAL	–15.7	–12.6	36.5	16.2	35.1	15.7	33.7	15.4	3045	682
GREELEY-WELD COUNTY AP	–22.1	–17.8	35.9	17.0	33.7	16.8	32.2	16.7	3655	357
PUEBLO MEMORIAL	–17.8	–14.1	36.9	16.8	35.5	16.6	33.9	16.4	3049	528
Connecticut										
BRADLEY INTL	–15.1	–12.3	33.0	22.9	31.3	22.1	29.8	21.3	3246	438
HARTFORD-BRAINARD AP	–13.2	–11.0	32.7	22.8	31.2	22.3	29.5	21.5	3056	479
IGOR SIKORSKY MEMORIAL	–11.4	–9.1	31.1	22.8	29.4	22.1	28.0	21.4	2906	477
WATERBURY-OXFORD AP	–16.0	–12.9	30.9	22.7	28.7	21.7	27.4	20.8	3564	260
WINDHAM AP	–15.8	–12.6	32.1	22.9	30.3	22.2	28.8	21.4	3306	357
Delaware										
DOVER AFB	–9.6	–7.4	33.6	24.3	32.2	23.8	30.7	23.3	2478	663
NEW CASTLE AP	–10.1	–7.9	33.5	23.9	31.9	23.2	30.5	22.7	2602	644
Florida										
CECIL FIELD	–1.0	1.1	35.6	24.8	34.4	24.6	33.3	24.4	647	1517
CRAIG MUNICIPAL	0.4	2.3	34.6	25.0	33.4	24.9	32.5	24.8	643	1525
DAYTONA BEACH INTL	2.0	4.2	33.7	25.0	32.7	24.9	31.8	24.8	404	1678
FT LAUDERDALE HOLLYWOOD INTL	8.8	11.1	33.2	25.7	32.6	25.7	32.1	25.7	69	2561
GAINESVILLE REGIONAL	–1.3	0.7	34.3	24.4	33.4	24.3	32.6	24.2	638	1483
HOMESTEAD AFB	7.8	10.1	32.9	26.2	32.4	26.1	32.0	26.0	80	2349
JACKSONVILLE INTL	–1.4	0.4	34.7	25.1	33.7	24.9	32.7	24.7	724	1461
JACKSONVILLE NAS	1.2	3.1	35.4	24.9	34.3	24.6	33.3	24.4	526	1811

Station	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
KENNEDY SPACE CENTER	4.0	6.2	33.2	25.6	32.5	25.6	31.8	25.5	292	1764
MACDILL AFB	3.8	6.1	34.1	25.8	33.4	25.6	32.8	25.5	273	2029
MAYPORT NAF	1.8	3.9	34.4	25.1	33.1	25.1	32.2	24.9	559	1645
MELBOURNE INTL	3.7	6.1	33.3	25.3	32.5	25.3	31.9	25.3	257	1929
MIAMI EXECUTIVE	7.6	9.8	33.8	25.5	33.0	25.4	32.5	25.3	91	2304
MIAMI INTL	9.3	11.5	33.3	25.3	32.7	25.3	32.1	25.3	63	2543
NAPLES MUNICIPAL	6.5	8.6	33.1	25.4	32.5	25.4	32.0	25.4	152	2115
ORLANDO EXECUTIVE	3.9	6.2	34.2	24.5	33.5	24.4	32.8	24.3	281	1968
ORLANDO INTL	3.5	5.7	34.3	24.7	33.5	24.6	32.8	24.4	294	1892
ORLANDO SANFORD INTL	2.7	4.9	34.7	24.3	33.8	24.2	32.9	24.1	343	1857
PAGE FIELD	6.0	8.1	34.2	24.8	33.5	24.8	32.9	24.8	148	2191
PALM BEACH INTL	7.0	9.2	33.2	25.4	32.5	25.4	31.9	25.4	116	2299
PANAMA CITY BAY COUNTY INTL	–0.1	2.1	33.8	24.9	32.8	24.9	32.3	24.9	690	1582
PENSACOLA INTL	–1.1	1.0	34.4	25.3	33.3	25.2	32.4	25.0	790	1503
PENSACOLA NAS	–1.3	0.6	33.9	26.0	32.9	25.8	32.2	25.6	819	1454
SARASOTA BRADENTON INTL	4.2	6.7	33.5	25.8	32.8	25.8	32.4	25.7	253	1932
SOUTHWEST FLORIDA INTL	5.1	7.4	34.1	24.8	33.5	24.8	32.8	24.7	170	2079
ST PETE-CLEARWATER INTL	5.7	7.5	33.4	25.4	32.8	25.3	32.4	25.2	246	2040
TALLAHASSEE REGIONAL	–3.2	–1.3	35.6	24.5	34.6	24.2	33.6	24.1	829	1479
TAMPA INTL	4.2	6.3	33.6	25.0	33.0	25.0	32.4	25.0	281	2005
TAYLOR FIELD	–1.3	1.0	34.0	24.0	33.0	24.0	32.6	23.9	579	1531
TYNDALL AFB	–0.3	1.9	32.9	26.0	32.3	26.0	31.7	25.9	736	1469
VENICE	5.4	7.7	31.2	24.7	30.5	25.0	30.1	25.1	265	1672
VERO BEACH REGIONAL	3.8	6.2	33.2	25.3	32.5	25.4	31.9	25.4	230	1922
Georgia										
ATHENS BEN EPPS AP	–5.2	–3.1	35.2	23.7	33.9	23.3	32.6	23.1	1531	1002

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB	MCWB	DB	MCWB	DB	MCWB	HDD	CDD 18.3
ATLANTA HARTSFIELD-JACKSON	–5.6	–3.0	34.4	23.4	33.1	23.2	32.0	22.9	1467	1056
ATLANTA REGIONAL	–7.0	–4.8	34.1	23.2	33.0	23.1	32.1	23.0	1668	877
AUGUSTA REGIONAL	–5.2	–3.3	36.3	24.4	34.9	24.2	33.7	24.0	1324	1152
COLUMBUS AP	–3.4	–1.4	35.8	23.7	34.6	23.5	33.5	23.4	1137	1311
DANIEL FIELD	–2.7	–1.1	36.0	23.6	34.4	23.1	33.2	23.0	1170	1294
DEKALB-PEACHTREE AP	–6.0	–3.6	34.5	23.1	33.2	23.0	32.3	22.6	1593	1009
DOBBINS AFB	–6.9	–4.1	34.0	23.5	32.8	23.4	31.8	23.1	1624	976
FULTON COUNTY AP	–6.0	–3.5	34.5	23.5	33.3	23.3	32.3	23.0	1559	981
HUNTER AAF	–2.3	–0.1	35.3	25.2	34.1	24.9	32.9	24.8	894	1433
LAWSON AAF	–5.3	–3.4	36.0	24.4	34.8	24.3	33.6	24.2	1284	1152
LEE GILMER MEMORIAL	–6.0	–3.3	33.6	23.0	32.5	22.9	31.3	22.5	1670	913
MIDDLE GEORGIA REGIONAL	–4.5	–2.5	35.9	24.1	34.7	23.9	33.5	23.7	1258	1196
MOODY AFB	–1.6	0.4	35.6	24.7	34.6	24.6	33.7	24.3	796	1482
RICHARD B RUSSELL REGIONAL	–7.0	–4.8	35.4	23.6	34.0	23.3	32.8	23.2	1683	987
ROBINS AFB	–4.0	–2.2	36.1	24.4	34.9	24.3	33.7	24.0	1186	1238
SAVANNAH HILTON HEAD INTL	–2.5	–0.6	35.3	25.0	34.0	24.9	32.9	24.6	957	1369
SW GEORGIA REGIONAL	–3.0	–1.3	36.0	24.4	34.8	24.3	33.7	24.1	970	1415
VALDOSTA REGIONAL	–2.4	–0.6	35.9	24.8	34.7	24.6	33.7	24.3	821	1459
Hawaii										
HILO INTL	16.4	17.1	29.8	23.3	29.3	23.2	28.8	23.0	0	1803
HONOLULU INTL	17.0	18.1	31.9	23.2	31.4	23.0	30.9	22.8	0	2587
KALAELOA	15.8	17.0	32.3	23.0	31.6	22.9	31.1	22.8	0	2341
KANEOHE MCAS	17.8	18.8	29.4	23.5	29.0	23.4	28.5	23.2	0	2328
Idaho										
BOISE AP	–12.6	–9.0	37.0	17.6	35.4	17.1	33.8	16.6	3008	559
CALDWELL INDUSTRIAL AP	–12.4	–9.1	36.1	19.0	34.0	18.2	32.6	17.7	3188	384

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
COEUR D'ALENE AP	–14.5	–12.0	32.9	17.3	31.4	17.0	29.0	16.2	3819	176
IDAHO FALLS REGIONAL	–21.4	–17.9	33.4	16.1	32.0	15.8	30.4	15.3	4262	160
LEWISTON-NEZ PERCE CO REGL	–10.6	–7.3	36.9	18.5	35.0	18.0	33.0	17.3	2802	482
MAGIC VALLEY REGIONAL	–13.6	–11.1	35.0	17.0	33.4	16.7	32.1	16.4	3349	431
POCATELLO REGIONAL	–18.9	–15.7	34.9	16.3	33.2	16.0	31.6	15.5	3856	244
Illinois										
ABRAHAM LINCOLN CAPITAL	–17.2	–13.9	33.7	24.8	32.4	24.2	31.1	23.4	2960	636
AURORA MUNICIPAL	–20.5	–17.4	32.6	23.4	31.2	22.9	29.7	22.2	3632	405
CHICAGO MIDWAY INTL	–17.5	–14.4	33.3	23.7	31.9	22.8	30.3	22.2	3250	587
CHICAGO O'HARE INTL	–18.3	–15.3	32.9	23.4	31.4	22.7	29.9	22.0	3439	490
CHICAGO ROCKFORD INTL	–20.8	–17.6	32.7	23.5	31.1	22.7	29.7	22.0	3661	437
DECATUR AP	–16.7	–13.7	33.9	24.8	32.6	24.2	31.3	23.5	2993	614
DUPAGE COUNT AP	–19.2	–16.4	32.4	23.7	31.0	23.1	29.2	22.1	3572	417
GLENVIEW NAS	–18.2	–15.1	34.3	23.9	32.3	23.0	30.6	22.3	3391	505
GREATER PEORIA REGIONAL	–18.3	–15.4	33.3	24.7	32.0	24.0	30.6	23.1	3185	587
QUAD CITY INTL	–19.7	–16.8	33.5	24.5	32.1	23.9	30.6	22.9	3384	549
QUINCY REGIONAL	–17.6	–14.7	34.0	24.7	32.4	24.1	30.9	23.4	3054	622
SCOTT AFB	–13.8	–11.1	35.1	25.4	33.7	25.0	32.4	24.4	2565	785
ST LOUIS DOWNTOWN AP	–13.0	–10.7	35.2	24.8	33.7	24.6	32.4	24.0	2538	796
U OF ILLINOIS WILLARD AP	–18.0	–15.1	33.0	24.2	32.0	23.8	30.5	23.0	3163	541
Indiana										
EVANSVILLE REGIONAL	–12.8	–9.7	34.5	24.5	33.2	24.2	32.0	23.7	2438	807
FORT WAYNE INTL	–18.0	–14.8	32.7	23.6	31.2	22.8	29.7	22.0	3321	459
GRISSOM AFB	–18.5	–14.7	32.6	24.1	31.1	23.3	29.8	22.7	3260	499
INDIANAPOLIS INTL	–16.4	–13.0	33.0	23.9	31.6	23.3	30.3	22.7	2916	614
MONROE COUNTY AP	–15.6	–12.3	33.0	23.9	32.0	23.8	30.6	23.0	2817	570

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
PURDUE UNIVERSITY AP	–17.4	–14.3	33.1	24.2	32.0	23.5	30.5	22.7	3070	554
SOUTH BEND INTL	–17.6	–14.3	32.4	23.3	30.9	22.4	29.4	21.7	3422	444
TERRE HAUTE INTL	–16.6	–12.9	33.6	24.5	32.3	24.2	31.0	23.4	2872	602
Iowa										
AMES MUNICIPAL	–21.4	–18.6	32.7	24.5	31.3	23.7	29.9	22.9	3681	449
ANKENY REGIONAL	–19.9	–17.2	33.9	24.2	32.4	23.9	31.0	23.2	3403	542
BOONE MUNICIPAL	–20.9	–17.7	32.9	24.7	31.9	24.3	30.1	23.0	3602	488
DAVENPORT MUNICIPAL	–21.6	–18.6	32.8	23.9	31.2	23.3	29.9	22.6	3597	488
DES MOINES INTL	–20.1	–17.5	33.8	24.5	32.1	23.9	30.6	23.0	3415	592
DUBUQUE REGIONAL	–22.3	–19.3	31.4	23.9	29.8	22.9	28.4	21.9	3912	356
SIOUX GATEWAY AP	–21.7	–19.1	33.8	24.0	32.3	23.5	30.8	22.8	3741	508
THE EASTERN IOWA AP	–22.3	–19.2	32.4	24.6	30.9	23.6	29.4	22.6	3753	430
WATERLOO MUNICIPAL	–23.1	–20.3	32.8	24.1	31.2	23.2	29.7	22.4	3898	427
Kansas										
COLONEL JAMES JABARA AP	–14.1	–11.7	37.8	23.1	36.2	23.3	34.0	23.1	2502	907
FORBES FIELD	–15.8	–12.8	37.2	24.4	34.9	24.1	33.0	23.7	2765	790
JOHNSON COUNTY EXECUTIVE	–15.4	–12.7	35.8	24.2	33.7	24.1	32.3	23.8	2687	785
LAWRENCE MUNICIPAL	–15.9	–13.0	37.3	24.8	35.3	24.3	33.4	24.1	2773	819
MANHATTAN REGIONAL	–16.7	–13.6	37.9	24.0	36.1	24.0	33.9	23.7	2858	826
MARSHALL AIRFIELD	–15.1	–12.6	38.1	23.9	36.0	24.0	34.2	23.8	2744	885
MCCONNELL AFB	–13.2	–10.6	37.9	22.6	36.2	23.0	34.3	23.0	2380	969
PHILIP BILLARD MUNICIPAL	–15.6	–12.8	36.8	24.4	34.9	24.4	33.2	23.9	2714	837
SALINA MUNICIPAL	–15.4	–12.7	38.9	23.1	37.1	23.2	35.1	22.9	2666	948
WICHITA EISENHOWER NATL	–13.5	–11.0	38.4	22.9	36.5	23.1	34.7	23.1	2469	968
Kentucky										
BLUE GRASS AP	–12.9	–9.9	33.1	23.4	31.8	23.1	30.5	22.6	2519	665

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
BOWLING GREEN AP	–10.9	–8.0	34.5	23.9	33.1	23.9	32.0	23.6	2211	819
BOWMAN FIELD	–11.8	–8.7	34.1	24.0	32.9	23.7	31.8	23.3	2309	826
CAMPBELL AAF	–11.1	–7.9	34.8	24.5	33.4	24.3	32.3	24.0	2096	897
CINCINNATI NORTHERN KY INTL	–14.5	–11.2	33.1	23.5	31.7	23.0	30.4	22.5	2732	619
HENDERSON CITY-COUNTY AP	–12.9	–9.8	34.1	24.6	32.9	24.4	32.3	24.0	2485	776
LAKE CUMBERLAND REGIONAL	–11.0	–7.8	34.5	23.7	32.9	23.3	32.2	23.0	2192	771
LOUISVILLE INTL	–11.7	–8.6	34.5	24.0	33.2	23.9	32.0	23.4	2254	891
Louisiana										
ALEXANDRIA ESLER REGIONAL	–3.3	–2.0	36.7	24.8	35.3	25.0	34.2	24.9	1104	1407
ALEXANDRIA INTL	–2.8	–1.2	36.3	24.9	35.1	25.0	33.9	24.8	1028	1477
BARKSDALE AFB	–4.1	–2.4	37.2	24.2	35.8	24.3	34.4	24.4	1243	1347
BATON ROUGE METROPOLITAN	–2.0	–0.2	34.9	25.2	34.0	25.2	33.2	25.0	876	1512
LAFAYETTE REGIONAL	–1.0	1.0	34.9	25.4	33.9	25.3	33.0	25.1	802	1587
LAKE CHARLES REGIONAL	–0.8	1.0	34.9	25.4	33.9	25.4	33.0	25.3	797	1583
LAKEFRONT AP	2.2	4.0	34.2	25.9	33.7	25.8	32.8	25.5	596	1881
LOUIS ARMSTRONG NEW ORLEANS	0.7	2.5	34.5	25.5	33.6	25.4	32.8	25.2	697	1667
MONROE REGIONAL	–3.7	–2.0	36.8	25.4	35.5	25.2	34.2	25.0	1213	1392
NEW ORLEANS NAS	–0.4	1.4	33.9	25.4	33.1	25.2	32.4	25.1	764	1516
SHREVEPORT DOWNTOWN AP	–3.1	–1.6	37.5	24.6	36.1	24.5	34.8	24.4	1207	1474
SHREVEPORT REGIONAL	–3.4	–1.7	37.3	24.3	35.9	24.4	34.6	24.4	1163	1451
Maine										
AUBURN LEWISTON MUNICIPAL	–21.1	–17.7	31.0	21.8	28.7	20.9	27.3	19.8	4214	174
BANGOR INTL	–21.7	–18.8	30.9	21.4	29.0	20.5	27.3	19.4	4230	200
BRUNSWICK NAS	–19.0	–16.5	30.1	21.3	28.2	20.5	26.8	19.5	3989	205
PORTLAND INTL JETPORT	–17.5	–14.9	30.4	21.8	28.5	21.0	26.8	20.1	3850	212
SANFORD SEACOAST REGIONAL	–21.1	–17.6	32.1	22.1	29.8	21.1	27.9	20.1	4124	203

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
Maryland										
ANDREWS AFB	–9.4	–7.4	34.5	23.9	32.8	23.3	31.4	22.7	2432	695
BALTIMORE-WASHINGTON INTL	–9.7	–7.6	34.5	23.8	33.0	23.4	31.5	22.6	2495	704
THOMAS POINT	–7.7	–5.5	30.5	24.7	29.4	24.4	28.4	24.0	2297	692
Massachusetts										
BARNSTABLE MUNICIPAL	–12.1	–9.2	29.0	22.7	27.5	22.0	26.3	21.3	3217	292
BOSTON LOGAN INTL	–13.1	–10.3	32.6	22.6	30.9	22.0	29.1	21.1	3062	431
BUZZARDS BAY	–10.5	–8.2	24.7	N/A	23.7	N/A	23.0	N/A	3006	188
CHATHAM MUNICIPAL	–11.0	–8.1	28.3	22.6	27.0	22.1	25.8	21.4	3110	274
LAWRENCE MUNICIPAL	–15.0	–12.3	32.5	22.8	31.0	22.2	29.0	21.2	3337	380
MARTHAS VINEYARD AP	–12.4	–9.8	28.9	22.5	27.5	21.9	26.2	21.2	3209	251
NEW BEDFORD REGIONAL	–13.0	–10.9	31.2	23.0	29.1	22.0	27.8	21.2	3206	326
NORWOOD MEMORIAL	–16.1	–12.8	32.6	23.1	31.1	22.5	29.1	21.3	3411	337
PLYMOUTH MUNICIPAL	–14.4	–12.1	31.5	22.8	29.6	22.1	27.9	21.1	3362	319
SOUTH WEYMOUTH NAS	–14.5	–12.0	32.9	23.2	31.0	22.4	29.3	21.5	3240	359
WORCESTER REGIONAL	–16.4	–13.8	29.9	21.6	28.4	20.8	27.0	20.0	3668	269
Michigan										
BISHOP INTL	–17.9	–15.3	31.9	23.0	30.3	22.1	28.9	21.2	3718	339
DETROIT COLEMAN YOUNG INTL	–14.9	–12.4	32.6	23.0	31.1	22.2	29.6	21.4	3321	491
DETROIT METRO WAYNE COUNTY AP	–16.0	–13.2	32.4	23.4	30.8	22.5	29.3	21.6	3370	456
GERALD R FORD INTL	–16.2	–13.7	31.8	22.8	30.3	22.0	28.8	21.1	3636	368
GROSSE ILE MUNICIPAL	–14.1	–12.3	32.1	23.6	30.0	23.2	28.6	22.6	3271	477
JACKSON COUNTY AP	–17.5	–14.8	31.4	22.9	29.9	22.1	28.5	21.2	3664	323
KALAMAZOO BATTLE CREEK INTL	–16.4	–13.6	32.3	22.8	30.9	22.1	29.1	21.2	3493	406
LANSING CAPITAL REGION INTL	–18.0	–15.2	31.7	22.9	30.1	22.0	28.6	21.1	3763	322
MBS INTL	–17.6	–15.2	31.9	22.8	30.2	21.8	28.7	21.1	3808	326

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
MUSKEGON COUNTY AP	–14.7	–12.5	30.1	22.3	28.7	21.5	27.5	20.9	3647	299
OAKLAND COUNTY INTL	–17.2	–14.8	32.1	22.8	30.2	21.7	28.7	20.9	3684	363
SELFRIDGE ANGB	–16.8	–14.0	32.2	23.4	30.3	22.3	28.8	21.5	3563	368
ST CLAIR COUNTY INTL	–17.8	–15.0	32.2	23.1	29.9	21.8	28.0	20.9	3778	254
WEST MICHIGAN REGIONAL	–14.0	–12.2	31.9	23.0	30.2	22.1	28.7	21.5	3454	368
WILLOW RUN AP	–17.2	–14.2	32.9	23.2	31.3	22.4	29.7	21.5	3523	407
Minnesota										
ANOKA COUNTY AP	–22.7	–20.3	32.3	23.8	30.9	23.1	28.8	22.0	4183	343
CRYSTAL AP	–23.1	–21.1	32.6	23.0	31.2	22.2	29.2	21.1	4222	402
DULUTH INTL	–27.3	–24.4	29.0	21.0	27.3	19.5	25.7	18.5	5159	121
FLYING CLOUD AP	–23.7	–21.3	32.7	23.4	31.2	22.6	29.4	21.6	4119	448
MANKATO MUNICIPAL	–24.6	–22.3	32.2	23.2	30.2	22.2	28.6	21.4	4281	349
MINNEAPOLIS-ST PAUL INTL	–23.7	–21.0	32.7	22.9	31.0	22.2	29.4	21.2	4154	434
ROCHESTER INTL	–24.7	–22.0	30.9	23.0	29.3	22.1	27.9	21.3	4351	293
SKY HARBOR AP	–23.6	–21.3	30.1	22.2	27.9	20.7	27.0	20.0	4756	172
SOUTH ST PAUL MUNICIPAL	–22.6	–20.2	32.7	22.8	31.2	22.0	29.2	21.0	4095	428
ST CLOUD REGIONAL	–27.1	–24.1	31.9	22.5	30.2	21.5	28.6	20.4	4681	269
ST PAUL DOWNTOWN AP	–23.3	–21.0	32.6	23.2	31.1	22.5	29.0	21.4	4147	418
Mississippi										
HATTIESBURG-LAUREL AP	–3.9	–2.4	35.9	24.3	34.0	23.9	32.9	23.8	1159	1263
JACKSON INTL	–4.6	–2.8	35.7	24.5	34.6	24.5	33.5	24.4	1262	1286
KEESLER AFB	–0.8	1.5	34.6	26.8	33.5	26.3	32.6	26.0	796	1556
KEY FIELD	–5.2	–3.3	35.6	24.3	34.4	24.4	33.3	24.3	1306	1201
MERIDIAN NAS MCCAIN FIELD	–5.3	–3.0	36.0	24.6	34.8	24.6	33.7	24.4	1302	1240
TUPELO REGIONAL	–6.9	–4.6	35.7	24.4	34.3	24.3	33.2	24.1	1617	1117
Missouri										

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
CAPE GIRARDEAU REGIONAL	–12.2	–9.0	34.7	25.0	33.5	24.8	32.4	24.4	2329	841
COLUMBIA REGIONAL	–15.8	–12.7	34.8	24.3	33.2	24.4	31.6	23.9	2732	709
CR WHEELER DOWNTOWN	–14.5	–12.1	36.3	24.5	34.5	24.3	33.0	24.0	2537	924
JEFFERSON CITY MEMORIAL	–14.2	–11.3	35.6	24.4	33.8	24.0	32.5	23.7	2541	802
JOPLIN REGIONAL	–12.9	–10.0	36.3	23.8	34.7	24.0	33.1	23.8	2247	927
KANSAS CITY INTL	–16.4	–13.6	35.6	24.7	33.7	24.5	32.1	24.1	2793	764
LAMBERT-ST LOUIS INTL	–13.6	–10.7	35.6	24.8	34.1	24.5	32.8	23.9	2446	931
SPIRIT OF ST LOUIS AP	–14.3	–11.3	35.3	25.1	33.8	24.6	32.4	24.0	2596	777
SPRINGFIELD-BRANSON REGIONAL	–13.9	–10.7	35.3	23.3	33.5	23.4	32.0	23.3	2460	781
Montana										
BERT MOONEY AP	–27.4	–22.8	31.1	14.1	29.3	13.6	27.6	13.3	5053	44
BILLINGS LOGAN INTL	–23.0	–19.6	34.9	17.0	33.0	16.6	31.1	16.3	3743	360
BOZEMAN YELLOWSTONE INTL	–26.2	–22.1	33.4	16.2	31.5	15.8	29.6	15.2	4540	132
GREAT FALLS	–25.5	–21.6	32.5	15.7	30.7	15.3	29.0	14.9	4281	185
GREAT FALLS INTL	–26.8	–23.0	33.6	16.1	31.7	15.7	29.8	15.2	4198	187
MALMSTROM AFB	–26.1	–22.5	34.7	17.1	32.6	16.4	30.8	15.8	3819	268
MISSOULA INTL	–19.7	–16.0	33.9	16.5	32.1	16.2	30.2	15.7	4085	187
Nebraska										
CENTRAL NEBRASKA REGIONAL	–19.5	–16.7	35.4	23.3	33.6	22.9	31.9	22.2	3384	586
EPPLEY AIRFIELD	–19.6	–17.0	34.9	24.4	33.2	24.1	31.6	23.2	3347	647
LINCOLN MUNICIPAL	–19.2	–16.7	35.9	23.8	34.1	23.6	32.4	23.1	3316	662
NORTH OMAHA AP	–21.2	–17.8	34.5	23.9	32.7	23.7	31.1	22.8	3323	607
OFFUTT AFB	–19.2	–16.8	35.0	24.7	33.0	24.3	31.7	23.6	3306	648
Nevada										
MCCARRAN INTL	–0.2	1.3	42.5	19.7	41.3	19.3	40.1	18.8	1090	1976
NELLIS AFB	–2.0	–0.2	42.9	19.6	41.8	19.3	40.5	18.8	1151	1919

Station	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
RENO TAHOE INTL	–10.5	–7.8	35.8	16.3	34.3	15.8	32.9	15.1	2756	484
New Hampshire										
CONCORD MUNICIPAL	–19.4	–16.6	32.2	21.8	30.5	21.0	29.0	20.3	3923	265
JAFFREY-SILVER RANCH AP	–19.0	–16.6	30.6	21.1	28.8	20.3	27.4	19.5	4044	211
MANCHESTER-BOSTON REGIONAL	–16.6	–13.8	32.9	22.1	31.4	21.4	29.8	20.7	3448	407
PORTSMOUTH INTL	–16.3	–13.5	32.0	22.5	30.0	21.7	28.2	20.9	3553	309
New Jersey										
ATLANTIC CITY INTL	–11.0	–8.6	33.5	24.0	31.8	23.2	30.3	22.6	2670	575
MCGUIRE AFB	–11.3	–8.9	33.8	24.1	32.4	23.6	30.9	22.9	2694	596
MILLVILLE MUNICIPAL	–11.3	–8.8	33.4	23.9	31.9	23.3	30.5	22.7	2692	587
MONMOUTH EXECUTIVE	–11.4	–8.9	32.8	23.3	31.3	22.6	29.1	21.9	2807	511
NEWARK LIBERTY INTL	–10.7	–8.4	34.6	23.6	32.9	22.8	31.3	22.2	2574	706
TETERBORO AP	–11.2	–8.8	33.7	23.4	32.2	22.7	30.7	22.0	2731	606
TRENTON MERCER AP	–11.2	–8.9	33.7	23.5	32.2	22.9	30.7	22.4	2731	587
New Mexico										
ALAMOGORDO-WHITE SANDS AP	–6.3	–4.0	37.7	17.5	37.0	17.6	35.1	17.3	1609	1061
ALBUQUERQUE INTL	–7.6	–5.6	35.3	15.5	34.0	15.4	32.8	15.3	2198	799
CANNON AFB	–10.2	–7.7	37.0	17.3	35.3	17.4	33.9	17.6	2066	801
CLOVIS MUNICIPAL	–11.0	–8.0	36.3	17.8	34.8	17.7	33.0	17.7	2252	693
FOUR CORNERS REGIONAL	–13.4	–11.0	35.5	15.3	34.0	15.0	32.8	14.9	2928	549
HOLLOMAN AFB	–7.4	–5.5	37.7	17.1	36.4	16.9	35.1	16.9	1787	1021
ROSWELL INTL AIR CENTER	–7.9	–5.8	38.4	18.0	36.9	18.2	35.7	18.1	1719	1098
WHITE SANDS	–7.6	–5.3	37.2	17.6	35.8	17.7	34.6	17.7	1637	1006
New York										
ALBANY INTL	–17.9	–15.2	31.6	22.5	30.0	21.7	28.6	21.0	3596	355
AMBROSE LIGHT	–10.1	–7.8	28.9	N/A	27.2	N/A	25.8	N/A	2694	400

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
BUFFALO NIAGARA INTL	–15.8	–13.7	30.2	21.8	28.8	21.1	27.5	20.5	3589	322
CHAUTAUQUA COUNTY AP	–17.5	–15.1	28.0	20.9	27.3	20.3	26.0	19.4	3992	169
DUTCHESS COUNTY AP	–16.3	–13.1	33.0	23.0	31.4	22.4	29.8	21.6	3335	403
ELMIRA CORNING REGIONAL	–17.8	–15.1	32.0	22.0	30.2	21.1	28.7	20.4	3737	261
GREATER BINGHAMTON AP	–17.8	–15.3	29.6	21.0	28.0	20.2	26.6	19.5	3907	224
GREATER ROCHESTER INTL	–16.2	–13.8	31.4	22.8	29.8	21.7	28.3	20.9	3592	317
JOHN F KENNEDY INTL	–21.0	–17.4	31.1	22.2	29.5	21.2	28.1	20.4	3884	269
LAGUARDIA AP	–9.9	–7.8	32.2	22.8	30.3	22.1	28.8	21.6	2654	563
LONG ISLAND MACARTHUR AP	–9.8	–7.6	33.6	23.3	32.0	22.5	30.5	21.9	2496	713
NIAGARA FALLS INTL	–11.2	–9.0	31.4	23.0	29.8	22.2	28.4	21.7	2888	466
ONEIDA COUNTY AP	–16.2	–13.9	31.0	22.5	29.5	21.7	28.0	20.9	3664	323
PLATTSBURGH INTL	–20.4	–17.1	30.6	22.5	29.0	21.4	27.7	20.6	3894	262
REPUBLIC AP	–22.6	–19.3	30.4	21.7	28.3	20.8	26.8	20.1	4186	208
STEWART INTL	–10.9	–8.3	32.2	23.2	30.2	22.2	28.7	21.8	2799	506
SYRACUSE HANCOCK INTL	–15.8	–12.7	32.3	22.3	30.5	21.9	28.9	21.0	3300	396
WESTCHESTER COUNTY AP	–18.2	–15.0	31.8	22.8	30.2	21.8	28.7	21.0	3608	347
North Carolina										
ALBERT J ELLIS AP	–6.4	–4.0	34.8	25.0	33.0	24.5	32.4	24.2	1639	965
ASHEVILLE REGIONAL	–9.2	–6.9	31.1	21.8	29.8	21.4	28.7	20.9	2264	476
CHARLOTTE DOUGLAS INTL	–5.8	–3.7	34.5	23.7	33.2	23.4	32.0	23.0	1689	939
FAYETTEVILLE REGIONAL	–5.1	–2.9	35.7	24.4	34.1	23.8	32.9	23.6	1503	1102
HICKORY REGIONAL	–6.7	–4.5	33.5	22.6	32.2	22.4	31.0	22.0	1919	766
NEW RIVER MCAS	–4.8	–2.9	33.9	25.6	32.6	25.1	31.5	24.7	1409	1069
PIEDMONT TRIAD INTL	–7.1	–5.1	33.6	23.4	32.4	23.0	31.2	22.6	1963	808
PITT-GREENVILLE AP	–6.2	–3.9	35.0	24.5	33.8	24.0	32.7	23.6	1663	1037
POPE AFB	–6.1	–3.9	36.2	24.6	34.8	24.3	33.2	23.8	1565	1130

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB	MCWB	DB	MCWB	DB	MCWB	HDD	CDD 18.3
RALEIGH-DURHAM INTL	–6.4	–4.3	35.0	24.2	33.6	23.9	32.3	23.5	1782	936
SEYMOUR-JOHNSON AFB	–5.2	–3.0	35.9	24.6	34.3	24.3	33.0	23.9	1492	1118
SIMMONS AAF	–5.3	–3.2	35.9	24.3	34.5	24.0	33.0	23.6	1523	1130
SMITH REYNOLDS AP	–6.6	–4.2	33.4	23.2	32.4	22.8	31.2	22.4	1898	816
WILMINGTON INTL	–4.0	–2.3	34.1	25.5	32.9	25.0	31.7	24.6	1313	1122
North Dakota										
BISMARCK MUNICIPAL	–27.5	–24.5	33.9	21.1	31.9	20.5	30.0	19.8	4696	294
GRAND FORKS AFB	–28.9	–26.4	32.0	22.3	30.1	21.2	28.5	20.3	5173	233
GRAND FORKS INTL	–29.7	–27.0	31.7	22.0	29.9	20.9	28.4	19.9	5202	232
HECTOR INTL	–28.2	–25.5	32.2	22.4	30.6	21.3	29.1	20.4	4856	306
MINOT AFB	–30.2	–27.4	32.5	20.5	30.6	20.0	28.7	19.1	5193	197
MINOT INTL	–27.8	–25.1	32.5	20.7	30.5	20.1	28.7	19.0	4886	239
Ohio										
AKRON-CANTON REGIONAL	–16.0	–13.2	31.4	22.6	30.0	21.9	28.6	21.0	3329	391
CINCINNATI MUNICIPAL LUNKEN	–13.2	–10.1	33.7	23.9	32.3	23.5	31.0	23.0	2642	624
CLEVELAND HOPKINS INTL	–15.2	–12.2	31.9	23.1	30.4	22.3	29.0	21.6	3223	437
FAIRFIELD COUNTY AP	–16.5	–12.5	32.5	23.3	31.3	22.9	29.9	22.0	3027	453
FINDLAY AP	–17.1	–13.9	32.4	23.0	31.0	22.3	29.5	21.5	3284	448
JMCOX DAYTON INTL	–16.5	–13.1	32.4	23.2	31.1	22.6	29.7	21.8	3045	529
MANSFIELD LAHM REGIONAL	–16.9	–13.9	31.1	22.7	29.8	21.9	28.5	21.2	3394	372
OHIO STATE UNIVERSITY AP	–15.3	–12.3	32.5	23.0	31.2	22.6	29.9	21.8	3028	516
PORT COLUMBUS INTL	–14.7	–11.7	32.9	23.2	31.7	22.6	30.4	21.9	2881	586
RICKENBACKER INTL	–14.0	–11.1	33.7	23.5	32.5	23.0	31.2	22.4	2792	632
TOLEDO EXPRESS AP	–16.9	–13.9	32.9	23.4	31.3	22.4	29.9	21.6	3361	449
WRIGHT-PATTERSON AFB	–16.0	–12.5	32.8	23.5	31.5	22.9	30.1	22.1	2979	516
YOUNGSTOWN-WARREN REGIONAL	–16.0	–13.3	31.2	22.5	29.8	21.5	28.5	20.8	3422	323

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
Oklahoma										
HENRY POST AAF	–9.1	–6.6	39.7	22.5	37.9	22.6	36.4	22.5	1752	1261
LAWTON-FORT SILL REGIONAL	–8.8	–6.7	40.3	22.6	38.8	22.7	37.4	23.0	1754	1319
RICHARD L JONES JR AP	–9.8	–7.5	38.7	24.1	37.2	24.6	35.6	24.5	1952	1158
STILLWATER REGIONAL	–11.0	–7.9	39.2	23.5	37.5	23.9	36.0	23.8	2006	1151
TINKER AFB	–10.1	–7.5	38.0	23.0	36.4	23.1	34.8	23.3	1882	1109
TULSA INTL	–10.3	–7.6	38.0	24.0	36.4	24.2	34.9	24.2	1917	1171
VANCE AFB	–12.1	–9.1	38.8	22.8	37.4	22.9	35.9	23.0	2178	1089
WILEY POST AP	–10.1	–7.4	38.0	23.0	36.8	23.1	35.1	23.1	1929	1173
WILL ROGERS WORLD AP	–9.7	–7.2	38.1	23.2	36.6	23.3	35.0	23.3	1900	1120
Oregon										
AURORA STATE AP	–3.8	–2.2	33.0	19.5	31.2	19.2	28.8	18.4	2478	208
CORVALLIS MUNICIPAL	–4.0	–2.5	33.7	19.4	32.1	18.9	29.7	18.0	2392	218
EUGENE AP	–5.1	–2.9	33.2	19.3	31.1	18.7	29.0	18.1	2591	157
MCMINNVILLE MUNICIPAL	–3.5	–2.1	33.4	19.3	31.3	18.9	29.0	18.2	2586	167
PORTLAND INTL	–3.9	–1.6	32.9	19.7	30.6	19.1	28.6	18.4	2351	248
PORTLAND-HILLSBORO AP	–5.2	–3.0	33.2	19.9	31.1	19.4	28.8	18.5	2662	153
ROBERTS FIELD	–14.9	–11.1	34.0	16.3	32.3	15.9	30.6	15.2	3634	132
ROGUE VALLEY INTL	–5.1	–3.3	37.2	19.5	35.3	18.7	33.5	18.1	2368	480
SALEM MUNICIPAL	–4.6	–2.6	33.4	19.4	31.2	18.8	29.1	18.1	2502	189
Pennsylvania										
ALLEGHENY COUNTY AP	–14.0	–11.7	31.8	22.3	30.3	21.6	29.0	20.9	2994	466
ALTOONA-BLAIR COUNTY AP	–14.2	–12.0	31.3	22.1	29.7	21.5	28.3	20.8	3267	344
BUTLER COUNTY AP	–16.1	–12.9	31.2	22.2	29.2	21.4	27.9	20.6	3389	312
CAPITAL CITY AP	–11.0	–8.8	33.5	23.3	31.9	22.5	30.5	22.0	2783	592
ERIE INTL	–14.4	–12.0	30.4	22.8	29.0	22.1	27.7	21.4	3353	371

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB	MCWB	DB	MCWB	DB	MCWB	HDD	CDD 18.3
HARRISBURG INTL	–11.3	–9.1	33.6	24.0	32.0	23.2	30.4	22.6	2794	622
LEHIGH VALLEY INTL	–12.9	–10.5	32.8	23.2	31.3	22.5	29.8	21.8	3046	473
NORTHEAST PHILADELPHIA AP	–10.4	–7.9	34.0	23.8	32.5	23.1	31.2	22.5	2607	663
PHILADELPHIA INTL	–9.7	–7.4	34.2	23.8	32.7	23.3	31.3	22.6	2458	754
PITTSBURGH INTL	–14.6	–12.0	31.8	22.2	30.3	21.5	29.1	20.9	3073	436
READING REGIONAL	–12.3	–9.9	33.7	23.5	32.1	22.9	30.5	22.2	2872	556
WASHINGTON COUNTY AP	–16.3	–12.9	31.3	21.8	29.7	21.1	28.2	20.4	3310	300
WILKES-BARRE SCRANTON INTL	–15.2	–12.5	31.7	22.1	30.1	21.2	28.6	20.5	3337	363
WILLOW GROVE NAS	–10.8	–8.6	33.3	23.3	31.9	22.6	30.5	21.9	2742	574
Rhode Island										
T F GREEN AP	–12.9	–10.4	32.3	22.9	30.4	22.1	28.8	21.3	3045	425
South Carolina										
CHARLESTON INTL	–2.5	–0.6	34.6	25.6	33.4	25.3	32.4	25.0	1025	1322
COLUMBIA METROPOLITAN	–4.8	–2.8	36.2	24.1	34.8	23.8	33.6	23.6	1351	1223
FLORENCE REGIONAL	–4.4	–2.6	35.6	24.8	34.2	24.4	33.0	24.1	1331	1174
FOLLY ISLAND	–0.2	1.7	30.8	25.5	30.1	25.5	29.5	25.4	1043	1198
GREENVILLE-SPARTANBURG INTL	–5.6	–3.6	34.6	23.1	33.2	23.0	31.9	22.6	1676	912
SHAW AFB	–4.6	–2.7	35.6	24.3	34.1	24.1	32.9	23.9	1353	1148
South Dakota										
ELLSWORTH AFB	–22.3	–19.3	35.1	19.1	33.0	18.7	31.2	18.4	3904	377
RAPID CITY REGIONAL	–22.7	–19.7	35.9	18.9	33.7	18.7	31.7	18.3	3927	366
SIOUX FALLS REGIONAL	–24.1	–21.4	33.0	23.2	31.4	22.7	29.8	21.8	4172	411
Tennessee										
CHATTANOOGA AP	–6.9	–4.6	35.0	23.6	33.7	23.5	32.5	23.1	1718	994
MCGHEE TYSON AP	–8.3	–5.8	33.7	23.3	32.4	23.1	31.3	22.7	1962	847
MCKELLAR-SIPES REGIONAL	–9.1	–6.7	35.0	24.7	33.8	24.7	32.7	24.4	1909	966

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
MEMPHIS INTL	–6.9	–4.6	35.9	25.0	34.7	24.7	33.6	24.4	1602	1259
MILLINGTON MUNICIPAL	–7.5	–4.9	37.4	26.8	36.1	26.0	34.1	25.2	1703	1181
NASHVILLE INTL	–9.2	–6.7	34.8	23.8	33.5	23.7	32.4	23.3	1939	964
TRI-CITIES REGIONAL	–10.3	–7.8	32.4	22.1	31.1	21.8	30.0	21.6	2321	576
Texas										
ABILENE REGIONAL	–6.6	–4.1	37.9	21.4	36.7	21.4	35.5	21.5	1358	1382
AL MANGHAM JR REGIONAL	–3.9	–2.5	37.3	24.3	36.0	24.3	34.0	24.2	1191	1367
AMARILLO RICK HUSBAND INTL	–12.2	–9.0	37.0	18.6	35.4	18.8	34.0	18.8	2246	817
ANGELINA COUNTY AP	–2.8	–1.3	37.2	24.5	35.8	24.7	34.6	24.6	1017	1505
AUSTIN-BERGSTROM INTL	–2.9	–1.0	37.9	23.4	36.8	23.5	35.7	23.6	908	1669
BROWNSVILLE INTL	3.7	5.9	35.4	25.5	34.7	25.5	34.1	25.5	283	2263
CORPUS CHRISTI INTL	1.5	3.5	36.0	25.3	35.1	25.4	34.3	25.3	459	2014
CORPUS CHRISTI NAS	2.9	5.3	33.8	26.3	33.1	26.3	32.7	26.3	392	2084
DALLAS EXECUTIVE	–3.9	–2.2	38.7	23.4	37.4	23.7	36.2	23.6	1173	1586
DALLAS FORT WORTH INTL	–4.8	–2.5	38.5	23.5	37.3	23.6	36.0	23.7	1201	1599
DALLAS HENSLEY FIELD NAS	–5.8	–2.7	37.6	24.2	36.4	24.1	35.1	23.9	1206	1513
DALLAS LOVE FIELD	–4.1	–1.8	38.6	23.7	37.4	24.0	36.2	23.8	1128	1680
DEL RIO INTL	–0.3	1.4	38.9	22.2	37.8	22.3	36.9	22.3	705	1963
DRAUGHON-MILLER CENTRAL TEXAS	–3.9	–2.2	37.8	23.3	37.2	23.3	36.0	23.3	1099	1537
DYESS AFB ABILENE	–7.2	–4.8	39.1	22.2	37.9	22.1	36.7	22.0	1394	1469
EASTERWOOD FIELD	–2.0	–0.1	37.8	24.1	36.6	24.2	35.5	24.1	871	1722
EL PASO INTL	–3.9	–2.0	38.4	17.9	37.1	17.6	35.9	17.5	1278	1401
FORT WORTH ALLIANCE AP	–6.0	–3.7	39.1	23.3	37.8	23.6	36.5	23.4	1332	1509
FORT WORTH NAS	–4.4	–2.2	39.2	22.8	37.9	23.1	36.7	23.2	1162	1654
FT WORTH MEACHAM INTL	–5.3	–2.9	38.6	23.3	37.4	23.6	36.2	23.5	1245	1543
GALVESTON SCHOLES INTL	2.5	4.2	33.3	26.2	32.7	26.2	32.2	26.2	550	1858

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
GEORGE BUSH INTERCONTINENTAL	–0.5	1.1	36.4	24.7	35.3	24.7	34.3	24.7	744	1735
GEORGETOWN MUNICIPAL	–3.0	–2.0	37.2	22.7	36.1	22.7	34.7	22.7	1082	1493
HOOKS MEMORIAL	–1.3	0.5	37.0	24.3	35.7	24.4	34.1	24.6	810	1676
HOUSTON ELLINGTON AP	1.2	2.8	36.0	25.6	34.9	25.8	33.9	25.8	648	1776
JACK BROOKS REGIONAL	–0.2	1.7	35.0	25.4	34.0	25.5	33.2	25.5	738	1638
KILLEEN MUNICIPAL	–3.2	–1.7	37.8	23.3	37.2	23.4	36.0	23.4	1049	1589
LACKLAND AFB	–1.3	0.6	38.0	23.4	37.2	23.4	36.1	23.4	755	1821
LAREDO INTL	2.3	4.0	40.4	23.6	39.1	23.5	38.0	23.5	435	2474
LAUGHLIN AFB	–0.7	1.3	40.2	22.2	38.9	22.5	37.7	22.5	655	2061
LONGVIEW EAST TEXAS REGIONAL	–3.6	–2.1	37.9	23.9	36.6	24.0	35.1	24.1	1178	1460
LUBBOCK INTL	–8.9	–6.6	37.5	19.0	36.1	19.4	34.8	19.4	1809	1064
MCALLEN INTL	3.7	5.6	38.0	24.4	37.2	24.7	36.3	24.6	296	2501
MCGREGOR EXECUTIVE	–4.0	–2.4	38.7	23.6	37.5	23.7	36.3	23.6	1159	1552
MCKINNEY NATL	–6.2	–3.9	38.4	23.5	37.3	23.9	36.0	23.8	1395	1414
MIDLAND INTL	–6.4	–4.2	38.4	19.3	37.0	19.5	35.8	19.6	1419	1329
NEW BRAUNFELS MUNICIPAL	–2.1	–0.3	37.9	23.2	37.0	23.3	35.9	23.3	839	1701
PORT ARANSAS	3.1	5.3	30.1	25.5	29.7	25.7	29.5	25.6	442	1716
RANDOLPH AFB	–2.0	0.0	37.9	23.2	37.0	23.2	35.9	23.2	808	1724
REESE AFB LUBBOCK	–9.6	–7.0	38.3	19.4	36.6	19.6	35.1	19.6	1768	1017
ROBERT GRAY AFF	–3.5	–1.3	38.0	22.8	37.2	22.9	36.0	22.9	1001	1614
SABINE PASS	0.2	2.3	31.7	25.2	30.8	25.3	30.3	25.3	793	1478
SAN ANGELO REGIONAL	–5.5	–3.4	38.7	21.1	37.5	21.0	36.3	21.0	1214	1468
SAN ANTONIO INTL	–1.2	0.6	37.4	23.0	36.4	23.1	35.4	23.2	767	1790
SAN MARCOS REGIONAL	–2.5	–1.0	37.7	23.4	37.1	23.4	35.9	23.4	901	1684
STINSON MUNICIPAL	–0.8	1.0	38.4	23.1	37.4	23.3	36.3	23.1	708	1888
VALLEY INTL	2.8	5.0	37.1	25.2	36.2	25.2	35.4	25.2	321	2280

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
VICTORIA REGIONAL	–0.4	1.4	36.6	24.7	35.5	24.8	34.5	24.8	647	1804
WACO REGIONAL	–4.1	–2.1	38.5	23.5	37.4	23.7	36.2	23.8	1116	1613
WICHITA FALL REGIONAL	–7.4	–5.2	39.9	22.6	38.4	22.6	37.0	22.7	1552	1414
WILLIAM P HOBBY AP	0.9	2.6	35.5	25.0	34.5	25.1	33.6	25.0	633	1790
Utah										
HILL AFB	–13.0	–11.0	34.4	16.0	33.0	15.7	31.8	15.5	3321	529
LOGAN-CACHE AP	–21.0	–17.6	34.9	16.5	33.5	16.1	32.2	15.8	3998	282
PROVO MUNICIPAL	–13.6	–11.2	34.8	16.9	32.9	16.7	32.1	16.5	3318	432
SALT LAKE CITY INTL	–12.3	–9.8	36.6	16.9	35.2	16.6	33.8	16.3	3037	701
ST GEORGE MUNICIPAL	–3.8	–2.4	41.2	19.0	39.7	18.4	38.0	17.9	1652	1512
Vermont										
BURLINGTON INTL	–21.9	–18.8	31.3	21.8	29.6	21.0	28.1	20.2	4015	292
Virginia										
DANVILLE REGIONAL	–7.6	–5.7	34.4	23.6	33.0	23.4	32.0	23.0	2027	800
DAVISON AAF	–9.4	–7.1	35.5	24.3	33.9	23.7	32.5	23.2	2349	754
DINWIDDIE COUNTY	–8.7	–7.0	36.7	25.0	34.9	24.5	33.0	23.8	2046	894
LANGLEY AFB	–6.2	–3.9	33.8	24.6	32.5	24.2	31.3	23.7	1897	880
LESSBURG EXECUTIVE	–9.9	–7.7	35.0	24.6	33.5	23.9	32.4	23.5	2462	748
LYNCHBURG REGIONAL	–9.0	–6.8	33.4	23.2	32.0	22.8	30.6	22.2	2329	618
MANSAS REGIONAL	–11.3	–8.8	33.9	23.5	32.6	23.3	31.3	22.7	2681	597
NEWPORT NEWS WILLIAMSBURG	–6.4	–4.3	34.7	25.0	33.3	24.5	32.2	24.0	1893	910
NORFOLK INTL	–5.1	–3.0	34.3	24.9	32.9	24.4	31.6	23.9	1758	953
NORFOLK NAS	–4.4	–2.4	34.7	25.1	33.3	24.6	32.2	24.2	1651	1049
OCEANA NAS	–5.6	–3.4	33.8	25.1	32.5	24.6	31.2	24.1	1812	886
QUANTICO MCAF	–8.3	–6.4	33.7	24.6	32.4	24.2	31.0	23.7	2294	764
RICHMOND INTL	–7.5	–5.5	35.1	24.3	33.7	23.9	32.3	23.4	2019	869

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
ROANOKE-BLACKSBURG REGIONAL	–8.4	–6.4	33.4	22.6	32.0	22.2	30.7	21.7	2201	688
RONALD REAGAN WASHINGTON NATL	–7.8	–5.8	34.8	24.2	33.3	23.7	31.9	23.1	2167	882
SHENANDOAH VALLEY REGIONAL	–11.2	–8.7	34.0	23.2	32.7	23.0	31.5	22.6	2482	627
VIRGINIA TECH MONTGOMERY EXEC	–11.7	–8.9	32.1	22.6	30.3	21.8	28.8	21.4	2666	437
WASHINGTON DULLES INTL	–10.4	–8.1	34.2	23.7	32.7	23.2	31.3	22.6	2551	660
Washington										
ARLINGTON MUNICIPAL	–7.0	–4.2	27.8	18.9	26.3	18.0	24.1	17.2	3001	34
BELLINGHAM INTL	–7.1	–4.6	26.3	18.5	24.6	17.7	22.9	16.8	2966	31
BREMERTON NATL	–5.2	–3.0	29.8	18.4	27.6	17.5	26.0	16.8	3134	54
FAIRCHILD AFB	–14.9	–11.6	33.2	16.7	31.7	16.3	29.8	15.8	3773	223
FELTS FIELD	–13.1	–9.9	34.7	18.3	32.8	17.6	31.1	17.0	3401	258
GRAY AFF	–6.7	–4.2	30.9	18.6	28.4	17.9	26.5	17.1	2869	85
KING COUNTY INTL AP	–3.4	–1.4	29.8	18.5	27.7	17.8	26.1	17.1	2419	149
MCCHORD AFB	–6.4	–4.2	30.2	18.4	28.0	17.6	26.2	16.9	2867	74
OLYMPIA REGIONAL	–6.5	–4.3	30.7	18.9	28.5	18.2	26.5	17.4	2987	61
PAINE FIELD	–3.9	–1.7	26.7	17.5	24.6	16.8	22.8	16.1	2884	45
PEARSON FIELD	–4.4	–2.7	32.6	19.1	30.6	18.8	28.3	18.1	2453	212
SANDERSON FIELD	–5.4	–3.4	30.8	18.4	28.3	17.9	26.1	17.1	3051	56
SEATTLE-TACOMA INTL	–3.6	–1.4	29.6	18.4	27.6	17.7	25.6	17.1	2614	109
SOUTHWEST WASHINGTON REGIONAL	–5.1	–2.9	31.1	19.6	28.0	18.6	26.3	17.7	2684	101
SPOKANE INTL	–15.0	–11.5	33.8	17.1	32.0	16.5	30.1	15.9	3682	256
TACOMA NARROWS AP	–2.6	–0.6	28.7	18.0	26.8	17.1	24.8	16.5	2662	81
TRI-CITIES AP	–12.1	–8.7	37.4	20.8	35.7	19.9	33.7	19.3	2747	453
WALLA WALLA REGIONAL	–11.7	–8.2	37.0	19.1	34.8	18.3	32.8	17.7	2672	519
WEST POINT	–1.4	0.6	21.4	16.1	20.1	15.7	19.0	15.3	2737	5
YAKIMA AIR TERMINAL	–13.2	–10.1	35.8	19.0	34.1	18.5	32.2	17.7	3247	309

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
West Virginia										
HUNTINGTON TRI-STATE AP	–11.8	–9.0	33.2	23.2	31.8	22.9	30.5	22.4	2443	635
MID-OHIO VALLEY REGIONAL	–13.0	–10.2	32.5	23.2	31.2	22.7	29.9	22.0	2714	524
YEAGER AP	–11.9	–9.0	32.9	22.8	31.6	22.6	30.3	22.1	2446	599
Wisconsin										
APPLETON INTL	–21.1	–17.9	31.3	24.0	29.4	22.7	27.9	21.6	4006	338
AUSTIN STRAUBEL INTL	–22.2	–19.4	31.1	23.1	29.4	22.1	28.0	21.2	4217	267
CENTRAL WISCONSIN AP	–23.9	–21.8	30.3	22.4	28.7	21.4	27.3	20.1	4613	201
CHIPPEWA VALLEY REGIONAL	–25.1	–22.2	32.2	22.8	30.4	21.6	28.9	20.7	4357	326
DANE COUNTY REGIONAL	–21.3	–18.5	31.9	23.4	30.3	22.4	28.8	21.7	3935	356
FOND DU LAC COUNTY AP	–21.3	–18.3	31.6	23.1	29.9	22.0	28.2	21.1	3985	334
GENERAL MITCHELL INTL	–18.3	–15.8	32.0	23.6	30.2	22.4	28.6	21.4	3709	385
KENOSHA REGIONAL	–19.1	–16.5	32.4	23.5	30.8	22.9	28.9	21.8	3742	349
LA CROSSE MUNICIPAL	–22.9	–20.1	33.0	23.9	31.3	22.8	29.9	21.9	3903	456
MANITOWOC COUNTY AP	–20.2	–17.5	29.3	22.1	27.7	21.3	26.4	20.2	4207	197
SHEBOYGAN	–18.8	–16.2	28.4	21.9	26.4	21.4	24.8	21.0	4027	189
SHEBOYGAN COUNTY MEMORIAL	–20.3	–17.7	31.4	23.3	29.2	21.9	27.7	21.1	4149	248
WAUSAU DOWNTOWN AP	–24.4	–21.7	30.9	22.1	29.1	20.8	27.7	19.8	4458	253
WITTMAN REGIONAL	–21.2	–18.7	31.4	23.1	29.7	22.0	28.0	21.2	4079	317
Wyoming										
CASPER-NATRONA COUNTY INTL	–22.5	–18.4	34.5	15.3	32.9	15.0	31.3	14.7	4060	261
CHEYENNE REGIONAL	–20.1	–16.4	31.9	14.5	30.5	14.2	28.9	14.0	3920	197
Canada										
Alberta										
BOW ISLAND	–29.3	–25.8	31.5	18.0	29.6	17.3	27.7	16.8	4780	111
CALGARY INTL	–28.5	–24.9	28.5	16.1	26.6	15.5	24.7	14.9	5109	37

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB	MCWB	DB	MCWB	DB	MCWB	HDD	CDD 18.3
CANADIAN OLYMPIC PARK UPPER	–27.3	–24.2	28.0	15.2	26.0	14.5	24.1	14.0	5039	41
EDMONTON CITY CENTRE AWOS	–28.9	–25.8	28.4	18.0	26.6	17.1	24.9	16.1	5235	73
EDMONTON INTL	–32.6	–29.2	27.8	17.9	25.9	17.2	24.3	16.1	5818	25
EDMONTON NAMAO AWOS	–30.1	–27.0	27.8	17.9	26.0	16.9	24.2	15.9	5589	37
FORT MCMURRAY CS	–34.7	–31.9	28.7	17.7	26.7	16.6	25.0	15.7	6247	42
GRANDE PRAIRIE	–35.9	–31.4	27.7	16.8	25.7	15.9	24.0	15.0	5930	26
LACOMBE CDA 2	–32.0	–28.3	28.1	18.2	26.1	17.3	24.4	16.3	5732	23
LETHBRIDGE CDA	–27.8	–24.5	31.7	16.9	29.7	16.3	27.7	16.0	4504	114
MEDICINE HAT RCS	–28.6	–25.2	33.1	17.0	31.1	16.4	29.2	16.1	4721	179
RED DEER	–32.0	–28.2	27.9	17.3	26.0	16.4	24.3	15.5	5727	23
SPRINGBANK	–31.4	–27.7	26.9	15.6	24.9	14.6	23.2	14.2	5720	4
British Columbia										
ABBOTSFORD	–7.7	–5.1	29.8	19.6	27.7	18.9	25.8	18.0	2911	81
AGASSIZ RCS	–7.4	–4.9	30.1	20.3	28.2	19.6	26.4	19.0	2857	116
BALLENAS ISLAND	–1.0	0.5	23.5	19.1	22.3	18.5	21.2	17.8	2651	57
COMOX	–4.7	–2.7	26.8	17.8	24.8	17.1	23.1	16.5	3089	57
DISCOVERY ISLAND	–1.3	1.2	22.7	N/A	20.7	N/A	19.1	N/A	2775	10
ENTRANCE ISLAND	–1.4	0.2	23.6	18.2	22.2	17.7	21.0	17.2	2693	58
ESQUIMALT HARBOUR	–2.6	–0.7	22.1	15.9	20.4	15.3	19.0	14.8	3042	6
HOWE SOUND PAM ROCKS	–2.8	–0.9	24.7	19.1	23.1	18.2	21.8	17.8	2649	77
KAMLOOPS	–19.5	–15.6	34.1	18.2	31.9	17.6	29.7	16.8	3533	278
KELOWNA	–17.3	–13.7	33.1	18.2	31.2	17.5	29.1	16.7	3894	140
MALAHAT	–5.8	–3.6	27.7	17.4	25.7	16.6	24.0	16.0	3254	96
PENTICTON	–13.4	–10.7	32.9	18.7	31.0	18.0	29.2	17.3	3426	228
PITT MEADOWS CS	–7.1	–4.7	30.2	19.8	28.2	19.1	26.2	18.3	2990	78
POINT ATKINSON	–1.8	–0.1	24.5	N/A	23.2	N/A	22.1	N/A	2433	103

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
PRINCE GEORGE	–30.2	–25.4	28.0	16.4	25.9	15.6	24.0	14.6	5136	22
SANDHEADS CS	–3.4	–1.2	22.2	N/A	21.2	N/A	20.2	N/A	2768	29
SUMMERLAND CS	–14.0	–10.8	32.9	17.7	31.0	17.2	29.1	16.6	3503	254
VANCOUVER HARBOUR CS	–2.9	–0.9	25.8	17.9	24.4	17.2	23.1	16.6	2683	71
VANCOUVER INTL	–6.1	–3.4	25.1	18.5	23.6	17.9	22.4	17.2	2911	46
VERNON	–16.5	–13.2	32.9	18.4	30.8	17.8	28.7	17.1	3771	205
VICTORIA GONZALES CS	–3.0	–0.7	24.6	16.9	22.2	16.0	20.5	15.2	2872	22
VICTORIA HARTLAND CS	–3.7	–1.6	28.5	18.7	26.6	17.9	24.8	17.3	2857	95
VICTORIA INTL	–4.0	–2.3	26.7	17.7	24.6	16.9	22.9	16.2	3007	26
VICTORIA UNIVERSITY CS	–2.7	–0.6	26.9	18.1	25.0	17.4	23.3	16.8	2772	36
WEST VANCOUVER	–5.8	–3.2	27.0	18.4	25.2	17.9	23.6	17.3	2999	76
WHITE ROCK CAMPBELL SCI	–5.3	–2.9	24.8	18.8	23.2	18.1	22.0	17.4	2788	31
YOHO PARK	–29.9	–26.6	25.5	13.7	23.4	13.0	21.3	12.2	6496	1
Manitoba										
WINNIPEG INTL	–32.0	–29.7	30.3	21.3	28.6	20.3	27.0	19.4	5758	159
New Brunswick										
FREDERICTON INTL	–23.2	–20.6	29.9	21.0	28.1	19.9	26.4	19.0	4585	143
MONCTON INTL	–22.2	–19.7	28.7	20.9	27.0	19.8	25.4	18.9	4665	111
SAINT JOHN	–22.3	–19.5	26.2	18.8	24.6	17.9	23.0	17.0	4692	33
Newfoundland and Labrador										
ST JOHN'S INTL	–15.1	–13.0	24.8	19.1	23.3	18.3	21.9	17.7	4794	33
Northwest Territories										
YELLOWKNIFE	–40.5	–38.3	25.4	16.0	23.7	15.2	22.2	14.6	8159	37
Nova Scotia										
HALIFAX STANFIELD INTL	–18.2	–16.1	27.9	20.4	26.2	19.4	24.6	18.6	4253	111
SHEARWATER	–17.2	–15.1	26.2	19.5	24.6	18.6	23.0	17.9	4183	72

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
SYDNEY	–17.7	–15.2	27.6	20.3	25.9	19.4	24.2	18.6	4496	88
Nunavut										
IQALUIT CLIMATE	–35.6	–34.1	18.0	12.6	14.8	11.2	12.6	9.8	9468	1
Ontario										
BEAUSOLEIL	–24.7	–21.1	29.9	23.3	28.1	22.1	26.5	21.3	4394	212
BELLE RIVER	–14.2	–11.9	31.5	24.0	29.8	23.3	28.2	22.4	3346	423
ERIEAU	–14.8	–12.6	26.8	22.9	25.9	22.2	25.0	21.7	3612	282
GUELPH TURFGRASS INSTITUTE	–21.4	–18.4	29.8	21.7	28.0	20.9	26.6	20.0	4434	153
HAMILTON INTL	–18.2	–15.5	30.6	22.5	29.0	21.7	27.4	20.9	3926	249
LONDON INTL	–18.2	–15.6	30.2	22.4	28.6	21.7	27.2	20.7	3943	239
NORTH BAY	–27.4	–24.5	27.9	20.1	26.3	19.2	24.9	18.4	5151	126
OTTAWA INTL	–24.2	–21.3	30.6	21.8	29.0	20.8	27.4	20.0	4483	241
PETERBOROUGH TRENT U	–22.4	–19.1	30.8	21.3	28.9	20.5	27.3	19.5	4323	177
PORT WELLER	–12.8	–10.8	29.1	22.8	27.6	22.1	26.2	21.4	3495	310
REGION OF WATERLOO INTL	–20.6	–17.4	30.6	21.9	28.9	21.2	27.2	20.3	4241	184
SAULT STE MARIE	–24.6	–21.5	28.4	21.1	26.6	20.0	25.1	19.0	4941	90
SUDBURY	–27.7	–24.6	29.0	20.2	27.2	19.0	25.6	18.0	5214	124
THUNDER BAY CS	–28.9	–26.2	29.2	20.2	27.4	19.0	25.6	18.1	5525	81
TIMMINS	–33.2	–29.8	29.6	20.0	27.6	18.5	25.8	17.8	5982	88
TORONTO BILLY BISHOP	–15.6	–13.1	28.4	21.6	26.8	21.1	25.3	20.5	3682	240
TORONTO BUTTONVILLE	–19.7	–16.8	31.6	22.4	29.7	21.3	28.0	20.5	4018	264
TORONTO PEARSON INTL	–18.0	–15.5	31.3	22.4	29.5	21.5	27.8	20.6	3837	304
TRENTON	–21.7	–18.6	29.1	22.1	27.7	21.3	26.3	20.5	4139	208
WINDSOR	–15.5	–13.0	32.0	23.1	30.4	22.3	29.0	21.5	3421	438
Prince Edward Island										
CHARLOTTETOWN	–20.2	–17.7	26.9	20.8	25.4	19.7	24.1	18.8	4572	108

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
Québec										
BAGOTVILLE	–29.8	–27.1	29.4	19.4	27.4	18.5	25.6	17.8	5607	102
BIG TROUT LAKE	–36.7	–34.4	27.0	18.7	25.3	17.7	23.5	16.9	7349	52
JONQUIERE	–30.2	–27.2	29.0	19.8	27.1	18.9	25.3	18.2	5508	98
LA BAIE	–30.2	–27.7	29.1	19.7	27.1	19.0	25.2	18.3	5680	71
LAC SAINT-PIERRE	–24.2	–21.3	27.9	21.1	26.4	20.3	25.2	19.6	4572	199
L'ACADIE	–24.3	–21.7	30.1	21.6	28.6	21.0	27.1	20.2	4409	229
L'ASSOMPTION	–25.6	–22.5	30.5	21.9	28.8	20.9	27.2	20.1	4604	211
LENNOXVILLE	–25.4	–22.2	29.4	21.5	27.9	20.7	26.5	19.8	4585	151
MONT-JOLI	–23.7	–21.4	26.9	19.8	25.1	18.7	23.6	17.8	5284	72
MONT-ORFORD	–28.5	–25.2	25.1	18.6	23.5	17.8	22.0	17.1	5659	53
MONTREAL MCTAVISH	–22.0	–19.2	30.1	21.9	28.6	20.9	27.2	20.1	4146	304
MONTREAL MIRABEL INTL	–26.0	–22.9	29.6	21.9	28.0	20.8	26.5	19.9	4727	179
MONTREAL ST-HUBERT	–23.5	–20.8	30.1	22.1	28.6	21.1	27.2	20.3	4414	235
MONTREAL TRUDEAU INTL	–23.1	–20.3	30.0	22.1	28.5	21.1	27.1	20.2	4317	272
NICOLET	–25.6	–22.8	28.8	22.3	27.2	21.3	25.9	20.4	4687	168
POINTE-AU-PERE INRS	–21.8	–19.2	23.0	18.6	21.5	17.6	20.2	16.6	5308	11
QUEBEC CITY JEAN LESAGE INTL	–24.5	–21.9	28.7	20.8	27.3	20.1	25.8	19.2	4879	137
SAINTE-FOY U LAVAL	–24.2	–21.6	29.1	20.6	27.5	19.6	26.0	18.7	4819	150
SHERBROOKE	–27.3	–24.2	28.8	21.1	27.3	20.2	25.9	19.4	4913	103
ST-ANICET 1	–24.6	–21.7	30.6	22.7	29.1	21.8	27.6	20.9	4417	218
STE-ANNE-DE-BELLEVUE 1	–23.8	–20.9	30.0	21.8	28.5	21.0	27.0	20.2	4404	231
TROIS-RIVIERES	–24.2	–21.6	27.3	21.3	26.1	20.8	25.0	20.2	4610	184
VARENNES	–23.5	–20.9	30.3	21.8	28.6	20.9	27.1	20.0	4477	207
Saskatchewan										
MOOSE JAW CS	–30.1	–27.4	31.8	18.6	29.7	18.1	27.7	17.4	5392	116

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
PRINCE ALBERT	–35.7	–32.4	28.9	18.9	27.0	18.0	25.4	17.0	6204	67
REGINA RCS	–32.3	–29.5	31.0	19.6	28.9	18.5	27.1	17.7	5774	111
SASKATOON INTL	–34.1	–31.1	30.2	18.9	28.2	18.1	26.4	17.4	5904	92
SASKATOON KERNEN FARM	–33.5	–30.6	30.6	17.7	28.6	16.9	26.8	16.1	5903	101
Yukon Territory										
WHITEHORSE	–39.7	–34.6	25.7	14.2	23.4	13.3	21.3	12.5	6771	7
Albania										
TIRANA RINAS	–2.8	–1.3	34.2	22.9	33.1	23.3	32.0	23.2	1532	687
Algeria										
CONSTANTINE BOUDIAF INTL	–0.5	0.5	38.9	20.2	37.0	20.2	35.0	19.8	1658	856
DAR EL BEIDA	1.8	2.9	35.2	22.4	33.5	22.5	32.0	22.5	984	897
ORAN INTL	2.2	3.8	34.3	21.1	32.5	21.3	31.0	21.5	901	913
Argentina										
CORDOBA INTL	–0.2	1.3	34.9	21.5	33.1	21.3	31.8	21.0	965	750
CORRIENTES INTL	4.2	5.9	36.9	24.4	35.8	24.5	34.2	24.2	396	1635
EL PLUMERILLO	–0.7	0.9	35.8	19.7	34.1	19.6	33.0	19.4	1217	918
EZEIZA INTL	–0.1	1.2	33.9	22.6	32.2	22.1	30.9	21.7	1181	668
JORGE NEWBERY INTL	4.2	5.8	31.2	23.2	30.0	23.0	28.8	22.4	891	761
MAR DEL PLATA	–1.2	0.0	31.1	21.2	29.1	20.4	27.2	19.9	1857	241
PARANA	2.5	3.8	34.5	23.1	33.0	22.6	31.8	22.2	833	914
POSADAS INTL	4.9	6.5	36.1	24.0	35.1	23.9	34.1	23.8	318	1772
RESISTENCIA INTL	1.8	3.8	37.2	24.1	36.0	24.3	34.7	24.2	465	1597
ROSARIO	–0.8	1.0	34.2	23.2	33.0	22.8	31.8	22.4	1012	806
SALTA AP	–1.1	0.2	33.1	18.4	31.7	18.7	30.1	18.7	928	574
SAN JUAN	–2.1	–0.6	38.0	19.7	36.6	19.6	35.2	19.2	1164	1157
SAN MIGUEL DE TUCUMAN	3.1	4.8	36.3	23.3	34.9	23.3	33.4	23.0	562	1261

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
SANTIAGO DEL ESTERO	–0.8	1.4	39.2	23.5	37.5	23.3	35.9	23.0	587	1498
SAUCE VIEJO	0.4	2.2	35.1	24.2	33.6	23.6	32.1	23.1	809	1045
Armenia										
YEREVAN EREBUNI	–13.1	–10.7	36.1	21.5	34.8	21.0	33.2	20.4	2740	771
Australia										
ADELAIDE INTL	3.9	5.0	36.2	18.3	33.9	17.9	31.8	17.5	1156	478
BRISBANE ARCHERFIELD	5.4	6.7	32.9	22.8	31.4	22.6	30.2	22.2	361	1068
BRISBANE INTL	5.8	7.2	30.9	22.6	29.7	23.0	28.9	22.5	333	1014
CANBERRA	–3.3	–2.1	34.0	17.9	31.8	17.3	29.7	16.8	2048	273
CANTERBURY RACECOURSE	3.8	4.8	32.5	20.0	30.3	20.2	28.5	20.0	894	518
GOLD COAST	6.0	7.8	29.2	23.3	28.5	23.1	27.9	22.7	317	943
GOLD COAST SEAWAY	9.6	10.8	30.5	23.0	29.3	22.7	28.3	22.5	186	1113
JANDAKOT AP	1.8	3.2	36.4	20.0	34.7	19.7	32.8	19.2	940	697
KENT TOWN	4.7	5.8	37.7	19.0	35.2	18.6	33.0	18.0	1064	604
LAVERTON RAAF	1.9	3.0	35.0	18.9	32.0	18.5	29.2	18.0	1656	238
MELBOURNE INTL	2.9	3.9	35.1	18.2	32.3	17.7	29.9	17.4	1663	268
MELBOURNE MOORABBIN	2.7	4.0	34.2	19.3	31.5	18.7	28.9	18.3	1587	232
MELBOURNE REGIONAL OFFICE	4.7	5.8	34.9	18.8	32.3	18.3	29.8	17.9	1258	351
MOUNT LOFTY	2.5	3.1	31.1	16.1	29.0	15.2	27.2	14.5	2554	184
NEWCASTLE NOBBYS SIGNAL	7.7	8.6	30.4	19.6	27.6	19.7	25.8	20.4	592	567
PERTH INTL	3.8	5.1	37.2	19.4	35.4	19.3	33.6	19.0	772	812
PERTH METRO	3.8	5.1	36.3	20.3	34.4	19.9	32.6	19.5	737	783
SCORESBY RESEARCH INSTITUTE	2.3	3.4	34.1	19.3	31.8	19.0	29.6	18.6	1636	271
SWANBOURNE	6.4	7.5	35.2	20.1	32.9	19.9	30.9	19.6	626	713
SYDNEY BANKSTOWN	3.3	4.4	33.8	20.6	31.4	20.5	29.5	20.1	911	559
SYDNEY INTL	6.4	7.2	32.9	19.3	30.2	20.1	28.5	20.0	669	662

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB	MCWB	DB	MCWB	DB	MCWB	HDD	CDD 18.3
SYDNEY OBSERVATORY HILL	7.3	8.0	31.1	19.8	28.9	20.2	27.3	20.3	632	616
SYDNEY OLYMPIC PARK ARCHERY	5.6	6.6	33.6	19.8	31.3	19.8	29.4	19.7	736	649
TUGGERANONG ISABELLA PLAINS	–3.7	–2.5	33.9	18.2	31.7	17.7	29.7	17.1	2061	284
WILLIAMTOWN	4.0	5.1	34.4	20.7	31.9	20.7	29.8	20.4	813	591
Austria										
GUMPOLDSKIRCHEN	–9.6	–7.5	31.3	21.5	29.4	20.6	27.7	19.6	2972	271
TULLN	–11.2	–8.4	31.7	21.5	29.8	20.6	28.0	19.7	3098	227
WIEN HOHE WARTE	–9.3	–7.1	31.2	21.9	29.3	20.9	27.7	20.0	2947	271
WIEN INNERE STADT	–8.0	–5.9	31.8	22.2	30.0	21.3	28.4	20.4	2683	386
WIEN SCHWECHAT	–10.3	–8.1	31.2	20.7	29.4	20.0	27.8	19.3	3061	243
Belarus										
BREST	–17.9	–14.2	30.2	19.9	28.3	19.0	26.5	18.2	3746	152
GOMEL	–20.6	–17.1	30.6	20.1	28.8	19.5	27.0	18.6	4092	179
GRODNO	–19.4	–15.9	28.8	19.8	26.8	18.9	25.1	17.8	4102	92
MINSK 1	–19.6	–16.2	29.2	19.7	27.5	18.8	25.9	18.0	4259	116
MOGILEV	–21.8	–18.6	28.9	19.8	27.0	18.9	25.2	18.2	4465	97
VITEBSK	–21.6	–18.3	28.6	19.7	26.8	18.9	25.0	17.9	4434	108
Belgium										
ANTWERP INTL	–6.5	–4.4	29.3	20.6	27.2	19.6	25.4	18.6	2771	109
BRUSSELS NATL	–6.5	–4.4	29.1	20.1	27.0	19.4	25.1	18.4	2860	98
UCCLE	–6.1	–4.2	29.0	19.8	27.0	19.0	25.1	17.9	2829	113
Benin										
COTONOU CAJEHOUN	22.0	22.8	32.9	27.1	32.2	27.1	32.1	27.1	0	3420
Bolivia										
COCHABAMBA AP	1.9	3.1	30.0	15.1	29.1	14.7	28.1	14.5	511	281
EL ALTO INTL	–5.0	–3.9	17.9	5.9	17.0	5.8	16.1	5.7	3897	0

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
VIRU VIRU INTL	9.2	10.9	34.9	23.6	33.9	23.8	33.0	24.0	87	2198
Bosnia and Herzegovina										
BJELASNICA	–18.7	–16.3	19.5	12.0	17.9	11.4	16.6	11.0	6013	1
SARAJEVO	–12.9	–10.0	33.1	19.7	31.1	19.6	29.2	19.2	3111	237
SARAJEVO-BJELAVE	–11.3	–8.9	33.0	19.6	31.0	19.2	29.1	18.6	2977	288
Brazil										
AFONSO PENA AP	2.9	5.0	30.9	20.1	29.9	20.2	28.8	20.2	627	592
ANAPOLIS AB	13.2	14.2	32.9	18.9	31.8	19.2	30.8	19.6	8	1632
ARACAJU AP	21.0	21.9	32.1	26.6	31.8	26.5	31.1	26.2	0	3082
BELEM VAL DE CANS INTL	22.8	22.9	33.2	25.9	33.0	25.8	32.2	25.8	0	3400
BELO HORIZONTE AP	11.1	12.2	32.9	20.1	31.9	20.2	31.0	20.1	22	1577
BRASILIA INTL	10.6	11.8	32.2	17.5	31.2	17.9	30.6	18.2	13	1426
CAMPO GRANDE AB	8.1	10.2	36.2	22.5	35.2	22.7	34.2	22.9	64	2532
CONFINS INTL	10.8	11.8	32.0	20.0	31.0	20.3	30.0	20.3	59	1243
CUIABA INTL	13.0	15.0	38.2	22.1	37.2	22.2	36.2	22.6	12	3343
EDUARDO GOMES INTL	21.8	21.9	35.9	26.3	35.0	26.0	34.2	26.0	0	3402
FLORIANOPOLIS INTL	7.8	9.7	32.1	25.2	31.0	25.0	29.9	24.4	216	1302
FORTALEZA INTL	22.8	23.0	32.1	24.9	31.9	24.8	31.2	24.6	0	3363
GOIANIA AP	12.5	13.8	35.2	19.7	34.2	20.2	33.2	20.5	3	2367
LONDRINA AP	7.9	9.9	34.0	21.7	33.0	21.9	32.0	22.1	119	1627
MACAPA INTL	22.8	22.9	35.1	26.5	34.9	26.5	34.1	26.6	0	3606
MACEIO INTL	18.8	19.1	33.0	25.5	32.2	25.1	31.9	25.0	0	2687
MANAUS AB	22.3	22.9	34.9	25.8	34.1	25.8	33.4	25.8	0	3455
NATAL AB	20.8	21.1	32.8	25.5	32.1	25.2	31.9	25.2	0	3114
PORTO ALEGRE INTL	3.9	5.8	34.9	24.7	33.1	24.1	31.9	23.7	488	1139
PORTO VELHO INTL	18.8	20.0	36.0	24.4	35.1	24.6	34.2	25.0	1	3343

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
RECIFE INTL	21.3	22.0	34.0	27.1	33.2	26.5	32.9	26.3	0	3371
RIO GALEAO TOM JOBIN INTL	14.9	15.9	36.9	25.0	35.2	24.8	34.1	24.8	6	2406
RIO SANTOS DUMONT AP	16.2	17.1	34.1	25.1	32.8	24.9	31.8	24.8	4	2268
SALVADOR INTL	20.8	21.2	32.3	26.6	32.0	26.5	31.2	26.2	0	3018
SAO LUIS INTL	22.8	23.1	33.9	26.1	33.2	25.8	32.9	25.6	0	3603
SAO PAULO CONGONHAS AP	9.0	10.2	32.2	20.2	31.1	20.2	30.1	20.2	212	1163
SAO PAULO INTL	7.8	9.1	32.8	21.5	31.2	21.3	30.2	21.2	220	1064
TERESINA AP	21.9	22.6	38.8	22.8	38.0	23.2	37.1	23.5	0	4030
VIRACOPOS INTL	8.9	10.2	33.2	20.9	32.2	21.0	31.2	21.0	99	1421
VITORIA AP	16.8	17.8	34.1	25.5	33.2	25.2	32.6	25.0	0	2609
Bulgaria										
CHERNI VRAH	–19.1	–17.2	17.3	11.0	15.9	10.5	14.7	10.1	6389	0
PLOVDIV	–10.2	–7.5	34.8	20.7	33.1	20.6	31.8	20.1	2531	559
SOFIA	–12.8	–10.0	33.0	19.0	31.0	18.7	29.2	18.5	3042	298
VARNA	–9.1	–6.9	31.9	22.3	30.2	22.1	29.0	21.6	2537	434
Burkina Faso										
BOBO DIOULASSO	18.4	19.6	38.1	20.3	37.4	20.3	36.6	20.4	0	3458
OUAGADOUGOU INTL	16.2	17.3	40.9	20.3	40.0	20.4	39.0	20.6	0	3867
Chad										
N'DJAMENA INTL	13.1	14.8	43.0	21.9	42.1	21.8	41.1	21.6	1	3892
Chile										
CERRO MORENO INTL	10.0	10.9	24.2	18.9	23.5	18.4	23.0	18.0	712	175
SANTIAGO PUDAHUEL INTL	–1.1	0.1	31.9	17.2	30.8	17.1	29.8	17.0	1486	264
China										
ANQING	–2.1	–0.9	35.7	27.2	34.7	27.1	33.6	26.7	1575	1328
ANYANG	–8.7	–6.8	35.4	23.2	34.0	23.9	32.7	23.9	2357	993

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
BAITA	–23.1	–20.1	32.1	17.4	30.5	17.1	29.1	16.8	4428	339
BAODING	–10.3	–8.4	35.3	22.6	33.7	22.9	32.4	23.0	2632	959
BAOJI	–6.1	–4.6	35.1	21.7	33.7	21.4	32.2	21.4	2342	816
BEIJING CAPITAL INTL	–11.2	–9.5	35.0	22.0	33.5	22.2	32.1	22.3	2845	871
BENGBU	–5.1	–3.5	35.6	26.5	34.4	26.1	33.0	25.4	1902	1146
BENXI	–22.3	–20.1	31.3	21.8	30.1	21.7	28.9	21.5	4091	496
CANGZHOU	–9.4	–7.7	34.2	23.2	33.0	23.5	31.9	23.4	2649	927
CHANGCHUN LONGJIA	–25.5	–23.1	31.0	20.6	29.6	20.9	28.3	20.6	4834	422
CHANGDE	–1.0	0.1	36.5	26.7	35.3	26.7	34.1	26.4	1476	1335
CHANGSHA	–1.2	0.0	36.4	26.1	35.3	26.1	34.2	26.0	1460	1389
CHAOYANG	–19.1	–16.9	33.7	21.1	32.1	21.2	30.9	20.9	3689	643
CHENGDE	–18.2	–16.4	33.1	20.4	31.5	20.4	30.2	20.2	3811	520
CHENGDU SHUANGLIU	0.8	1.9	33.9	25.0	32.8	24.5	31.2	23.9	1352	1018
CHONGQING JIANGBEI INTL	–20.4	–18.6	32.9	19.5	31.2	19.1	29.9	18.7	4218	445
DALIAN INTL	2.8	3.8	37.2	25.0	35.9	25.1	34.5	25.0	1171	1301
DANDONG	–16.1	–14.1	30.0	23.6	28.6	23.0	27.5	22.6	3610	458
DATONG	–20.7	–18.8	32.0	17.5	30.4	17.1	29.0	17.0	4201	356
DEZHOU	–8.3	–6.8	34.2	24.3	32.9	24.3	31.9	24.0	2496	966
FUZHOU CHANGLE INTL	4.6	5.8	35.6	26.7	34.4	26.5	33.2	26.3	703	1641
GANYU	–7.1	–5.5	33.3	26.4	31.8	25.8	30.5	25.5	2306	858
GUANGZHOU BAIYUN INTL	5.8	6.9	35.9	26.2	34.9	26.1	33.9	26.1	385	2106
GUIYANG LONGDONGBAO INTL	–3.1	–1.8	30.3	21.2	29.3	21.0	28.3	20.8	1734	656
HAIKOU	10.7	12.3	35.1	26.8	34.2	26.7	33.5	26.6	104	2528
HANGZHOU XIAOSHAN INTL	–2.1	–1.0	36.6	26.3	35.5	26.3	34.2	26.2	1561	1293
HARBIN	–27.8	–25.5	31.4	20.4	29.9	20.9	28.6	20.6	5218	400
HEFEI LUOGANG	–4.2	–2.9	35.6	27.7	34.4	27.3	33.2	26.8	1822	1193

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
JINAN TSINAN	–8.4	–6.6	35.1	23.2	33.8	23.4	32.6	23.1	2266	1079
JINGDEZHEN	–1.3	–0.1	36.2	26.4	35.2	26.3	34.2	26.0	1326	1426
JINGZHOU JIANGLING	–1.7	–0.6	35.0	27.7	34.1	27.2	33.1	26.6	1577	1241
JINZHOU	–16.0	–14.1	31.8	21.8	30.5	21.7	29.3	21.5	3494	618
JIXI	–24.8	–22.9	30.5	20.6	28.9	20.3	27.5	20.1	5226	285
KUNMING WUJIABA	0.7	1.9	28.0	16.4	27.0	16.4	26.0	16.6	1151	356
LANZHOU	–11.3	–9.8	32.6	18.0	31.1	17.4	29.7	16.8	3064	451
LIANGJIANG	1.0	2.2	35.1	25.4	34.1	25.3	33.1	25.3	1030	1503
LINGXIAN	–10.6	–8.6	35.1	23.6	33.6	23.9	32.2	24.0	2579	921
LIUZHOU	3.4	4.7	35.3	25.6	34.5	25.6	33.7	25.5	701	1889
MENGJIN	–6.6	–5.2	35.0	22.0	33.5	22.3	32.1	22.4	2193	931
MUDANJIANG	–26.5	–24.4	31.3	21.1	29.8	20.5	28.3	20.2	5149	345
NANCHANG CHANGBEI INTL	–0.7	0.4	35.9	26.6	34.9	26.6	33.9	26.4	1361	1464
NANJING LUKOU	–4.8	–3.2	35.7	26.7	34.4	26.5	33.1	26.1	1856	1133
NANNING WUXU INTL	4.8	6.1	35.0	26.2	34.1	26.1	33.2	25.9	493	1959
NEIJIANG	2.5	3.6	35.3	26.0	34.1	25.5	32.8	25.1	1218	1160
QINGDAO INTL	–8.2	–6.8	32.8	23.8	31.1	23.7	29.9	23.2	2494	800
QINGJIANG	–6.0	–4.1	33.8	27.1	32.7	26.5	31.5	25.7	2093	964
QIQIHAR SANJIAZI	–28.1	–26.0	31.9	20.7	30.2	20.3	28.8	20.1	5397	407
SHANGHAI BAOSHAN	–2.1	–0.7	35.3	26.6	34.0	26.5	32.8	26.2	1597	1193
SHANGHAI HONGQIAO INTL	–2.9	–1.2	35.9	27.1	34.2	27.1	33.1	26.7	1600	1253
SHANTOU	7.2	8.7	34.2	27.1	33.2	27.0	32.2	26.7	337	1885
SHAOGUAN	2.2	3.5	35.3	25.8	34.4	25.7	33.5	25.5	774	1729
SHENGYANG TAOXIAN	–24.1	–21.9	31.9	22.9	30.8	22.9	29.8	22.3	4149	562
SHENYANG	–23.1	–20.7	31.5	23.1	30.3	22.5	29.3	22.2	4112	546
SHENZHEN BAO'AN INTL	7.0	8.5	34.0	26.3	33.1	26.3	32.4	26.2	252	2219

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
SHIJIAZHUANG	–8.3	–6.7	36.1	21.9	34.4	22.7	33.0	22.9	2423	1042
SIPING	–23.4	–21.3	31.0	21.4	29.8	21.4	28.7	21.1	4469	480
TAI SHAN	–16.8	–14.7	22.7	17.2	21.7	17.4	20.9	17.7	4471	46
TAIYUAN WUSU INTL	–14.9	–12.9	33.5	19.8	32.1	19.9	30.9	19.6	3191	559
TANGSHAN	–13.5	–11.5	33.5	23.0	32.1	23.0	31.0	22.7	2971	803
TIANJIN	–10.6	–8.8	34.4	23.2	33.0	23.3	31.8	23.0	2728	934
TIANJIN BINHAI INTL	–11.0	–9.1	34.3	23.2	33.1	23.1	32.0	23.0	2759	921
URUMQI DIWOPU	–24.1	–21.9	35.2	17.9	34.0	17.7	32.8	17.4	4299	774
WEIFANG	–10.7	–9.1	34.4	24.1	33.0	24.0	31.6	23.6	2693	814
WENZHOU	1.3	2.8	33.9	27.3	32.9	27.0	32.0	26.7	1076	1306
WUHAN TIANHE	–2.5	–1.1	36.1	27.6	35.0	27.3	34.0	27.0	1599	1327
WUHUXIAN	–3.1	–1.8	36.2	27.4	35.1	27.1	33.8	26.7	1699	1227
WULUMUQI	–22.1	–20.0	33.4	16.3	31.9	16.1	30.4	15.8	4346	543
XIAMEN GAOQI INTL	6.8	7.8	34.8	26.3	33.8	26.3	32.8	26.1	452	1771
XIANYANG	–8.1	–6.2	36.2	23.0	34.9	22.9	33.2	22.7	2358	906
XIHUA	–5.6	–4.1	35.2	25.6	33.9	25.8	32.7	25.2	2067	1026
XINGTAI	–7.3	–5.9	35.9	22.3	34.4	22.8	33.0	23.1	2327	1062
XINING	–17.3	–15.5	27.6	15.1	26.0	14.3	24.5	13.6	4199	49
XINYANG	–4.6	–3.3	34.8	26.4	33.6	25.9	32.4	25.3	1891	1070
XINZHENG INTL	–6.4	–5.0	35.3	23.5	34.0	23.9	32.8	23.9	2157	1001
XUZHOU	–6.4	–4.7	34.8	25.8	33.6	25.4	32.4	24.8	2127	1039
YANGJIANG	7.0	8.3	33.1	26.5	32.2	26.3	31.5	26.2	279	2037
YANJI	–22.3	–20.2	31.1	21.5	29.4	20.9	27.9	20.3	4735	296
YICHANG	–1.0	0.1	35.9	26.6	34.6	26.0	33.3	25.5	1472	1224
YINCHUAN	–16.4	–14.2	32.7	18.8	31.4	18.6	30.1	18.0	3449	512
YINGKOU	–17.6	–15.6	30.5	24.0	29.4	23.5	28.5	23.1	3629	615

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB	MCWB	DB	MCWB	DB	MCWB	HDD	CDD 18.3
YUEYANG	–1.2	0.0	34.5	27.2	33.7	26.8	32.9	26.6	1466	1334
YUNCHENG	–8.7	–6.8	36.5	22.4	35.1	22.5	33.7	22.2	2321	1045
ZHANGJIAKOU	–16.9	–15.2	33.1	18.7	31.5	18.6	30.0	18.4	3707	545
ZHANJIANG	7.6	9.0	33.9	26.6	33.1	26.6	32.4	26.6	221	2229
ZHAOQING GAOYAO	6.3	7.5	35.1	26.1	34.3	26.0	33.4	26.0	381	2087
ZUNYI	–0.7	0.4	32.7	22.7	31.6	22.5	30.6	22.3	1635	856
Colombia										
ALFONSO BONILLA ARAGON INTL	17.8	18.0	32.2	22.1	31.7	22.0	31.0	21.9	0	2196
ELDORADO INTL	3.6	5.0	21.2	13.4	20.8	13.3	20.1	13.2	1666	0
ERNESTO CORTIZZOS INTL	22.8	23.1	34.2	27.3	33.8	27.2	33.1	27.0	0	3673
JOSE MARIA CORDOVA INTL	10.1	11.0	23.9	15.9	23.2	15.7	23.0	15.6	392	24
RAFAEL NUNEZ AP	23.2	23.9	33.1	27.6	32.2	27.2	32.1	27.1	0	3631
Congo										
BRAZZAVILLE MAYA MAYA INTL	18.0	18.9	34.2	24.6	33.5	24.6	32.9	24.5	0	2847
Costa Rica										
JUAN SANTAMARIA INTL	16.8	17.3	30.8	20.8	30.0	20.5	29.2	20.4	0	1836
Côte d'Ivoire										
ABIDJAN	21.2	22.0	32.9	27.5	32.2	27.2	31.8	27.0	0	3243
Croatia										
ZAGREB MAKSIMIR	–9.8	–7.0	32.6	21.5	30.9	20.9	29.3	20.3	2712	352
ZAGREB PLESO	–11.1	–8.2	32.8	21.8	31.1	21.2	29.5	20.7	2826	317
Cuba										
CAMAGUEY INTL	14.9	16.2	33.8	23.6	33.1	23.8	32.4	23.8	4	2678
HAVANA JOSE MARTI INTL	10.1	12.0	33.1	25.0	32.7	25.0	32.1	25.0	30	2303
SANTIAGO ANTONIO MACEO INTL	18.5	19.5	32.1	25.4	31.5	25.4	31.1	25.4	0	2865
Czech Republic										

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	**99.6%**	**99%**	**DB**	**MCWB**	**DB**	**MCWB**	**DB**	**MCWB**	**HDD**	**CDD 18.3**
BRNO-TURANY	–12.1	–9.8	30.8	20.2	29.0	19.4	27.2	18.6	3371	192
OSTRAVA MOSNOV	–14.9	–11.9	30.4	20.2	28.4	19.5	26.7	18.6	3551	127
PRAHA-KBELY	–12.6	–10.0	29.7	19.5	27.8	18.9	26.1	18.2	3407	143
PRAHA-LIBUS	–12.0	–9.5	30.6	19.2	28.7	18.6	26.8	17.8	3378	155
PRAHA-RUZYNE	–13.1	–10.4	29.6	19.2	27.7	18.5	25.8	17.8	3633	104
Denmark										
DROGDEN FYR	–5.3	–4.0	22.3	18.4	21.2	17.8	20.2	17.2	3406	30
KOEBENHAVNS KASTRUP	–6.9	–5.2	25.6	18.3	24.1	17.7	22.6	17.0	3513	54
ROSKILDE	–9.1	–7.0	25.9	18.3	24.1	17.7	22.7	17.0	3712	33
VAERLOSE	–9.8	–7.1	26.6	18.4	24.9	17.9	23.0	17.2	3764	40
Dominican Republic										
LAS AMERICAS INTL	18.0	18.9	33.0	26.4	32.2	26.3	32.0	26.2	0	2896
SANTO DOMINGO	19.8	20.5	32.6	27.2	32.1	27.1	31.6	27.0	0	3057
Ecuador										
JOSE JOAQUIN DE OLMEDO INTL	18.9	19.2	33.0	23.9	32.1	24.0	31.8	24.0	0	2777
QUITO PARQUE BICENTENARIO	6.8	7.3	21.9	11.8	21.1	11.9	20.8	11.9	1408	0
Egypt										
ALEXANDRIA INTL	7.0	8.0	33.2	22.4	31.9	23.3	30.9	23.7	452	1352
ASSIUT	4.7	5.8	41.1	20.6	39.8	20.5	38.4	20.2	474	2114
CAIRO INTL	7.9	8.9	38.2	21.2	36.9	21.5	35.7	21.6	344	1887
LUXOR INTL	5.8	6.9	43.2	22.8	42.2	22.6	41.2	22.4	264	2843
PORT SAID	9.8	10.8	32.2	25.4	31.2	25.4	30.9	25.4	276	1619
PORT SAID EL GAMIL	9.6	10.7	31.9	25.4	31.1	25.3	30.4	25.0	308	1528
Estonia										
TALLINN	–18.5	–15.1	26.7	19.1	24.8	18.0	23.0	17.1	4559	41
Finland										

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
HELSINKI VANTAA	–21.2	–18.0	27.1	18.1	25.2	17.2	23.8	16.4	4699	53
ISOSAARI	–17.4	–14.0	22.7	18.9	21.5	18.3	20.4	17.5	4485	31
France										
CAP COURONNE	–2.9	0.4	30.7	22.6	29.5	22.3	28.3	21.8	1578	567
CAP FERRAT	4.0	5.2	29.1	22.4	28.1	22.4	27.1	22.1	1270	560
CAP POMEGUES	–1.4	1.8	28.6	22.0	27.3	21.9	26.3	21.5	1523	457
LYON-BRON	–5.6	–3.9	33.1	19.8	31.2	19.6	29.5	19.2	2372	368
LYON-SAINT EXUPERY	–6.0	–4.2	32.6	19.9	30.7	19.7	28.9	19.2	2464	332
MARSEILLE PROVENCE	–2.5	–1.1	32.8	21.1	31.5	20.8	30.2	20.5	1616	644
NICE COTE D'AZUR	1.9	3.1	29.5	22.6	28.5	22.4	27.7	22.2	1383	547
PARIS CHARLES DE GAULLE	–5.1	–3.4	30.8	19.9	28.7	19.1	26.7	18.4	2555	172
PARIS LE BOURGET	–4.7	–3.0	31.1	19.8	28.9	19.1	26.9	18.4	2491	168
PARIS ORLY	–5.0	–3.2	31.1	20.0	29.0	19.4	27.1	18.6	2556	183
PARIS-MONTSOURIS	–3.1	–1.8	31.2	20.1	29.1	19.5	27.1	18.5	2293	235
TOULOUSE BLAGNAC	–3.8	–2.2	33.2	20.7	31.2	20.2	29.6	19.7	2021	399
TRAPPES	–4.9	–3.3	30.2	19.6	28.0	18.9	26.1	18.1	2668	138
VELIZY-VILLACOUBLAY	–4.9	–3.2	30.0	19.5	28.0	18.9	26.1	18.1	2700	155
Gabon										
LIBREVILLE INTL	21.9	22.4	31.8	27.4	31.1	27.2	30.9	27.1	0	3014
Gambia										
BANJUL INTL	16.6	17.3	37.8	20.3	36.1	20.2	35.0	21.0	0	3141
Georgia										
TBILISI	–6.0	–4.1	35.0	21.7	33.5	21.4	32.0	21.2	2286	713
Germany										
BERLIN DAHLEM	–12.0	–9.1	29.3	19.0	27.3	18.2	25.6	17.4	3390	118
BERLIN SCHONEFELD	–13.5	–10.5	29.9	19.1	27.9	18.2	26.1	17.5	3485	112

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
BERLIN TEGEL	–12.4	–9.2	30.0	18.7	28.0	18.0	26.2	17.1	3317	147
BERLIN TEMPELHOF	–11.8	–9.2	30.0	18.9	28.0	18.2	26.2	17.5	3283	147
BREMEN	–9.4	–7.3	28.9	19.5	26.9	18.7	25.0	17.8	3360	87
CELLE	–10.4	–7.9	30.2	19.0	28.2	18.3	26.3	17.5	3226	127
DRESDEN	–13.3	–10.3	29.8	18.8	27.7	18.2	25.9	17.5	3386	135
DUSSELDORF	–9.9	–6.8	29.6	19.6	27.8	18.7	26.1	17.9	2928	139
ESSEN MULHEIM	–9.9	–6.9	28.2	19.3	26.6	18.4	24.8	17.6	3178	103
FRANKFURT AM MAIN	–8.8	–6.5	31.4	19.1	29.3	18.7	27.6	18.1	3026	194
FURSTENFELDBRUCK	–15.1	–12.1	29.1	18.9	27.1	18.1	25.2	17.2	3706	82
GUTERSLOH	–8.8	–6.1	30.2	19.2	28.0	18.6	26.0	17.9	3068	122
HAMBURG FUHLSBUTTEL	–11.6	–8.9	27.8	18.9	25.9	18.1	24.0	17.2	3513	61
HANNOVER	–12.7	–9.7	28.9	19.4	27.0	18.5	25.1	17.6	3368	80
HEIDELBERG	–8.2	–5.8	32.1	20.4	30.2	19.7	28.2	18.7	2721	276
ITZEHOE	–9.6	–7.3	28.4	18.7	26.1	18.3	24.1	17.7	3486	62
KOLN BONN	–8.3	–6.2	30.3	19.6	28.2	18.8	26.3	18.0	3053	117
LEIPZIG HALLE	–13.3	–10.4	29.8	19.2	27.7	18.5	25.9	17.7	3393	120
LEIPZIG-HOLZHAUSEN	–11.0	–8.2	30.3	19.3	28.3	18.4	26.5	17.9	3169	153
MUNICH	–13.0	–10.0	29.9	19.1	27.9	18.6	26.1	17.9	3492	108
NORVENICH	–7.7	–5.3	30.7	19.5	28.4	18.9	26.4	18.0	2893	131
NURNBERG	–14.4	–10.9	30.2	18.5	28.3	17.9	26.5	17.0	3506	128
POTSDAM	–12.6	–10.0	29.7	18.9	27.7	18.3	25.9	17.7	3437	119
QUICKBORN	–9.7	–7.4	28.3	18.9	26.2	18.5	24.3	17.7	3461	56
ROTH	–13.1	–10.1	31.0	19.3	28.9	18.5	27.0	17.8	3541	115
STUTTGART FILDERSTADT	–12.7	–10.0	29.3	18.9	27.6	18.4	25.8	17.7	3489	106
STUTTGART SCHNARREN	–11.5	–9.0	29.6	19.6	27.8	18.6	26.1	17.9	3152	160
WUNSTORF	–9.5	–7.1	30.2	19.2	28.1	18.6	26.1	17.7	3119	127

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
Greece										
ATHINAI HELLINIKON	1.8	3.3	35.8	21.1	34.2	21.0	33.0	21.1	1098	1152
ELEFSIS	0.8	2.1	36.9	20.6	35.2	20.4	34.1	20.1	1217	1185
THESSALONIKI MAKEDONIA	–3.0	–1.3	34.8	21.7	33.1	21.7	31.9	21.2	1763	854
Guatemala										
LA AURORA INTL	10.9	11.9	28.1	17.8	27.1	17.9	26.2	17.8	62	706
Honduras										
RAMON VILLEDA MORALES INTL	17.8	18.8	36.9	25.7	35.8	26.0	34.9	26.0	0	3206
TONCONTIN INTL	11.8	13.0	32.0	19.3	31.0	19.6	30.1	19.6	11	1510
Hong Kong										
HONG KONG INTL	8.8	10.1	34.0	26.5	33.2	26.3	32.8	26.2	180	2346
HONG KONG OBSERVATORY	9.6	10.9	32.2	26.5	31.7	26.4	31.2	26.3	237	1976
Hungary										
BUDAORS	–11.2	–9.0	31.0	20.1	29.3	19.7	27.8	19.2	3072	246
BUDAPEST FERIHEGY	–11.9	–9.1	33.0	22.0	31.1	20.8	29.2	19.9	3105	286
BUDAPEST PESTSZENTLORINC	–9.9	–7.8	33.1	20.4	31.3	19.8	29.6	19.2	2896	372
India										
AHMEDABAD	10.8	12.1	42.5	23.0	41.2	22.9	40.0	22.9	11	3497
AKOLA	12.2	13.6	43.2	21.9	42.1	21.6	41.0	21.6	1	3572
AURANGABAD	10.8	12.1	40.1	22.8	39.2	22.7	38.2	22.4	6	2802
BANGALURU	15.3	16.0	34.2	19.9	33.5	19.8	32.6	19.8	0	2160
BELGAUM	13.0	14.2	36.3	19.2	35.3	19.3	34.4	19.4	0	2224
BHOPAL	9.5	10.8	41.8	21.9	40.6	21.6	39.4	21.5	61	2740
BHUBANESHWAR	13.9	15.0	39.1	27.1	37.7	26.9	36.5	26.7	1	3380
BIKANER	6.1	7.5	44.2	21.5	42.9	21.9	41.6	22.4	177	3464
CHENNAI INTL	19.9	20.8	38.9	25.9	37.4	25.8	36.2	25.8	0	3830

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
COIMBATORE INTL	18.3	19.2	36.3	22.0	35.5	22.3	34.7	22.6	0	3139
CWC VISHAKHAPATNAM WALTAIR	20.0	20.8	33.8	27.2	33.1	27.6	32.6	27.5	0	3448
DEVI AHILYA BAI HOLKAR INTL	9.4	10.8	40.7	20.0	39.6	20.0	38.4	19.9	44	2639
GUWAHATI INTL	10.8	11.8	34.8	27.1	34.0	27.0	33.2	26.9	57	2428
GWALIOR	5.9	7.0	43.6	23.2	42.4	23.2	41.1	23.1	192	3025
HYDERABAD BEGUMPET AP	13.6	14.9	40.6	21.7	39.2	21.7	38.1	21.7	1	3103
JABALPUR	8.3	9.6	42.5	20.7	41.3	20.7	40.1	20.9	84	2848
JAIPUR	7.1	8.5	42.4	21.3	41.2	21.4	40.0	21.4	166	2983
JAMSHEDPUR	10.1	11.3	42.2	22.5	40.7	22.8	39.1	23.2	24	3094
JODHPUR	8.8	9.9	42.6	21.3	41.3	21.7	40.1	21.9	76	3379
KOLKATA BOSE INTL	11.3	12.4	37.8	27.2	36.7	27.2	35.7	27.0	20	3118
KOZHIKODE	22.6	23.1	34.4	28.0	33.9	27.7	33.4	27.4	0	3583
LUCKNOW	6.7	7.9	42.2	23.1	40.9	23.0	39.2	23.7	193	2808
MANGALURU INTL	20.8	21.5	34.4	24.9	33.8	24.9	33.3	24.8	0	3337
MUMBAI SHIVAJI INTL	16.8	18.1	35.9	22.7	34.9	23.0	34.0	23.3	0	3476
NAGPUR AMBEDKAR INTL	11.4	12.8	44.2	22.6	43.0	22.6	41.9	22.3	6	3318
NELLORE	20.5	21.2	40.7	27.0	39.3	27.1	38.1	26.9	0	4103
NEW DELHI INDIRA GANDHI INTL	5.8	6.9	43.2	22.4	42.0	22.3	40.8	22.4	292	2971
NEW DELHI SAFDARJUNG	6.0	7.0	42.3	23.0	40.8	23.2	39.5	23.4	267	2823
PATIALA	5.0	6.1	41.8	25.1	40.3	24.9	38.7	24.9	401	2452
PATNA	7.8	9.0	41.2	23.1	39.8	23.2	38.1	23.9	145	2892
PUNE INTL	9.8	10.9	38.2	19.9	37.2	19.8	36.2	19.8	7	2375
RAJKOT	11.8	13.2	41.1	22.4	40.0	22.2	38.9	22.7	6	3451
SOLAPUR	15.4	16.9	41.1	22.6	40.0	22.8	39.0	22.5	0	3514
SURAT	14.1	15.4	37.9	22.5	36.5	22.9	35.2	23.1	1	3425
THIRUVANANTHAPURAM	22.1	22.8	34.0	25.9	33.4	25.8	32.9	25.7	0	3422

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB	MCWB	DB	MCWB	DB	MCWB	HDD	CDD 18.3
TIRUCHIRAPPALLI	20.0	20.8	39.1	26.0	38.2	25.8	37.7	25.7	0	4049
Indonesia										
BALI NGURAH RAI INTL	21.9	22.8	32.5	26.6	32.1	26.5	31.7	26.4	0	3382
HASANUDDIN INTL	20.2	21.1	34.3	24.1	33.8	24.3	33.1	24.7	0	3304
JUANDA INTL	21.0	21.8	34.1	24.4	33.5	24.5	33.0	24.7	0	3493
MEDAN POLONIA INTL	22.5	22.8	34.2	26.0	33.8	26.0	33.1	26.0	0	3454
MINANGKABAU INTL	21.4	22.0	32.2	25.9	31.9	25.9	31.5	25.8	0	3167
SAM RATULANGI INTL	20.6	21.4	33.1	24.4	32.6	24.5	32.1	24.7	0	3089
SOEKARNO HATTA INTL	22.2	22.8	34.0	25.5	33.2	25.6	33.0	25.7	0	3469
SYARIF KASIM II INTL	22.0	22.4	34.6	26.4	34.1	26.4	33.7	26.3	0	3520
Iran, Islamic Republic of										
ABADAN	4.0	5.5	47.9	22.5	46.9	22.3	45.9	22.0	416	3313
AHVAZ	4.8	6.0	47.9	23.1	46.9	22.9	45.8	22.6	429	3326
ARAK	–15.8	–11.6	36.5	16.1	35.3	15.8	34.1	15.4	2424	895
BANDAR ABBASS INTL	9.1	10.8	41.9	23.9	40.1	25.3	38.9	25.8	74	3252
BANDAR ANZALI	1.2	2.6	30.8	25.4	30.1	25.1	29.4	24.8	1503	889
HAMEDAN	–18.0	–14.3	35.6	16.8	34.5	16.2	33.3	15.8	2832	556
ISFAHAN SHAHID BEHESHTI INTL	–8.1	–6.1	39.1	17.1	38.1	16.6	36.9	16.4	2015	1056
KASHAN	–5.0	–2.5	42.0	19.6	40.8	19.2	39.6	18.8	1481	1848
KERMAN	–7.1	–5.2	38.1	16.1	37.0	15.7	36.0	15.4	1617	1031
MASHHAD INTL	–9.2	–6.1	37.2	17.8	36.1	17.6	34.9	17.2	2049	1047
MEHRABAD INTL	–3.6	–1.9	38.8	18.1	37.4	17.9	36.2	17.6	1592	1548
SHAHID ASHRAFI ESFAHANI	–7.9	–5.6	39.9	17.7	38.8	17.4	37.5	16.7	2054	1018
SHIRAZ SHAHID DASTGHAIB INTL	–2.2	–1.0	39.2	17.8	38.2	17.4	37.2	17.0	1371	1425
TABRIZ INTL	–11.8	–9.2	35.9	16.8	34.2	16.4	33.0	16.1	2646	823
URMIA	–12.0	–9.5	33.2	17.7	32.0	17.7	30.8	17.3	2880	457

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	**99.6%**	**99%**	**DB**	**MCWB**	**DB**	**MCWB**	**DB**	**MCWB**	**HDD**	**CDD 18.3**
ZAHEDAN INTL	–5.1	–3.2	39.1	16.4	38.0	16.1	37.0	15.4	1181	1469
ZANJAN	–14.3	–11.4	34.3	16.0	33.0	16.0	31.6	15.6	2938	454
Ireland										
CASEMENT	–3.1	–1.6	22.7	17.4	21.1	16.6	19.9	15.9	3148	7
DUBLIN	–2.7	–1.2	21.9	17.0	20.5	16.3	19.3	15.6	3164	4
Israel										
TEL AVIV BEN GURION	5.8	7.0	35.1	20.6	33.2	22.1	32.2	22.8	522	1438
TEL AVIV SDE DOV	7.3	8.7	31.4	23.4	30.4	24.2	29.9	24.2	488	1339
Italy										
BARI KAROL WOJTYLA	0.9	2.0	34.0	22.4	32.1	22.2	30.9	21.8	1482	689
BOLOGNA	–4.2	–2.9	34.4	22.4	33.0	22.2	31.8	21.8	2130	682
CATANIA FONTANAROSSA	1.5	2.9	34.4	23.2	32.8	23.1	31.2	22.8	1099	829
CATANIA SIGONELLA	1.0	2.1	37.1	22.2	35.4	22.1	33.9	22.0	1076	990
FIRENZE PERETOLA	–3.0	–1.2	35.2	21.8	33.9	21.7	32.2	21.1	1667	726
GENOVA SESTRI	1.2	2.9	29.9	23.0	28.9	23.4	28.0	23.2	1356	647
GRAZZANISE	–0.9	0.2	32.9	23.7	31.7	23.5	30.2	23.3	1534	634
MILANO LINATE	–4.8	–3.2	33.2	23.7	32.0	23.0	30.8	22.4	2142	634
NAPOLI CAPODICHINO	1.1	2.3	33.0	23.1	31.8	23.0	30.8	23.0	1276	791
PALERMO FALCONE-BORSELLINO	6.8	7.8	33.1	22.4	31.1	23.0	29.9	23.6	799	974
PRATICA DI MARE	0.8	2.0	31.0	23.1	30.0	23.3	29.0	23.5	1349	610
ROMA CIAMPINO	–1.1	0.1	33.9	21.7	32.6	21.6	31.1	21.2	1573	681
ROMA LEONARDO DA VINCI	–0.2	0.9	31.2	21.9	30.1	22.3	29.1	22.2	1482	572
TORINO BRIC DELLA CROCE	–5.0	–3.2	28.2	20.6	27.0	20.2	25.9	19.6	2600	283
TORINO CASELLE	–5.8	–4.1	30.9	22.3	29.8	21.7	28.4	20.9	2437	399
TRIESTE	–1.8	0.0	31.7	23.3	30.3	23.1	29.3	22.5	1752	665
Jamaica										

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
NORMAN MANLEY INTL	22.2	22.9	33.2	26.0	33.0	26.0	32.3	25.8	0	3586
Japan										
AKITA	–4.9	–3.9	31.6	24.3	30.1	23.7	28.6	23.1	2796	519
ASAHIKAWA	–17.4	–15.2	29.6	22.3	28.1	21.2	26.7	20.4	4271	245
ASHIYA	–0.9	0.1	32.4	25.8	31.2	25.8	30.2	25.5	1711	843
ATSUGI NAS	–0.9	0.1	33.1	25.5	32.0	25.0	30.9	24.8	1671	893
CHIBA	0.4	1.2	32.5	25.7	31.5	25.4	30.5	25.1	1623	886
FUJISAN	–28.6	–26.7	11.9	5.2	10.4	4.7	9.0	4.2	8881	0
FUKUOKA	–0.1	1.0	34.0	25.6	33.0	25.5	32.0	25.0	1532	1060
FUKUYAMA	–2.6	–1.6	34.0	25.3	33.0	25.2	32.0	25.0	1851	966
FUSHIKI	–2.4	–1.5	33.5	24.9	32.0	24.9	30.5	24.5	2198	739
FUTENMA	11.1	11.9	32.2	26.4	32.0	26.4	31.2	26.3	186	1870
GIFU	–3.2	–2.2	34.8	25.6	33.1	25.1	32.0	24.7	1972	923
HAMAMATSU	–0.8	0.1	33.0	25.6	31.2	25.3	30.2	25.0	1602	894
HIMEJI	–2.1	–1.3	33.5	25.5	32.5	25.2	31.5	24.9	1876	928
HIROSHIMA	–0.7	0.2	33.8	25.4	32.8	25.2	31.9	24.8	1643	1045
IIZUKA	–1.8	–0.7	33.6	25.6	32.6	25.4	31.5	25.1	1733	947
IRUMA	–3.1	–2.1	34.2	25.3	33.0	25.0	31.2	24.5	2005	786
KADENA AB	9.1	10.8	33.1	26.8	32.2	26.7	32.0	26.6	216	1881
KAGOSHIMA	1.4	2.6	33.5	25.8	32.6	25.6	31.8	25.4	1085	1293
KANAZAWA	–1.2	–0.5	33.2	24.8	32.1	24.7	31.0	24.4	2013	824
KANSAI INTL	1.8	2.8	33.0	25.4	32.0	25.2	31.1	25.1	1521	1073
KOBE	0.1	1.2	33.2	25.1	32.1	24.9	31.1	24.7	1580	1079
KOCHI	–0.7	0.3	32.9	25.3	32.0	25.1	31.2	24.9	1383	1059
KOMATSU	–2.0	–1.0	33.2	24.6	32.0	24.5	30.9	24.4	2098	757
KUMAGAYA	–2.1	–1.2	35.5	25.5	34.0	25.1	32.5	24.5	1858	900

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
KUMAMOTO	–1.6	–0.5	34.5	25.3	33.5	25.1	32.5	24.8	1498	1158
KURE	0.0	0.9	32.5	25.2	31.6	24.9	30.7	24.6	1606	994
KYOTO	–0.8	0.1	35.0	24.7	33.9	24.4	32.7	24.1	1743	1064
MATSUYAMA	0.0	0.9	33.4	24.8	32.6	24.6	31.7	24.4	1567	1026
MINAMITORISHIMA	18.0	18.7	31.9	26.3	31.4	26.2	31.0	26.0	0	2749
MIYAZAKI	–0.1	1.1	33.8	25.6	32.6	25.6	31.5	25.4	1244	1103
NAGANO	–6.7	–5.4	32.9	23.6	31.5	23.2	30.1	22.6	2718	653
NAGASAKI	0.8	1.9	32.8	25.5	31.8	25.4	30.9	25.2	1356	1072
NAGOYA	–2.0	–1.0	35.1	25.0	33.9	24.8	32.8	24.5	1782	1048
NAHA	12.8	13.1	32.2	26.4	32.0	26.4	31.2	26.5	117	2042
NARA	–2.1	–1.4	34.1	24.9	33.0	24.7	31.9	24.4	1943	883
NAZE	9.5	10.4	32.9	26.0	32.2	26.0	31.6	25.9	348	1617
NIIGATA	–1.7	–0.9	32.9	25.1	31.6	24.7	30.2	24.3	2233	737
NYUTABARU	–1.1	0.1	32.9	25.6	31.2	25.7	30.2	25.6	1361	962
OITA	–0.4	0.7	33.5	25.3	32.5	25.2	31.4	24.9	1533	978
OKAYAMA	–1.1	–0.2	34.4	25.2	33.5	24.9	32.4	24.7	1729	1073
OMAEZAKI	0.2	1.2	30.3	25.9	29.6	25.6	28.9	25.2	1454	844
ONAHAMA	–2.3	–1.3	29.1	24.2	28.0	24.0	27.1	23.5	2139	504
OSAKA	0.7	1.6	34.4	24.8	33.4	24.6	32.4	24.4	1534	1161
OSAKA INTL	–1.2	–0.2	34.9	25.5	33.8	25.2	32.8	24.9	1725	1067
OTARU	–9.5	–8.3	28.2	22.2	26.6	21.2	25.2	20.6	3697	225
OZUKI	–0.2	0.8	32.2	25.8	31.2	25.8	30.8	25.8	1704	887
SAPPORO	–9.9	–8.6	29.2	22.6	27.7	21.6	26.3	20.7	3576	298
SENDAI	–3.6	–2.6	31.4	24.5	29.9	24.0	28.5	23.3	2486	501
SHIMOFUSA	–2.0	–0.9	33.6	25.8	32.2	25.3	31.0	25.1	1812	829
SHIMONOSEKI	1.6	2.7	32.2	25.7	31.3	25.4	30.5	25.2	1431	998

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
SHIZUHAMA	–0.2	0.8	32.2	25.8	31.0	25.8	30.0	25.4	1522	869
SHIZUOKA	–0.2	0.9	32.9	25.3	31.6	25.1	30.6	24.8	1446	934
SUMOTO	0.0	0.9	31.8	25.4	30.8	25.2	29.8	24.9	1742	866
TADOTSU	–0.1	0.9	33.6	25.0	32.7	24.8	31.7	24.6	1641	1032
TAKAMATSU	–0.3	0.6	34.4	25.2	33.4	25.0	32.3	24.9	1641	1065
TOKUSHIMA	0.6	1.5	33.3	25.5	32.3	25.3	31.3	25.0	1531	1032
TOKYO	0.9	1.7	33.5	25.2	32.4	24.9	31.4	24.5	1556	968
TOKYO INTL	0.9	1.9	32.9	25.8	31.9	25.4	30.8	25.2	1576	901
TOYAMA	–2.4	–1.5	33.8	25.4	32.5	25.2	31.1	24.7	2142	788
TSUIKI	–2.0	–1.0	32.8	25.9	31.2	25.8	30.2	25.5	1852	835
UTSUNOMIYA	–4.1	–3.1	33.6	25.4	32.2	25.0	30.8	24.4	2134	746
WAKAYAMA	0.5	1.4	33.4	24.7	32.4	24.7	31.4	24.6	1547	1065
YOKOHAMA	0.7	1.5	32.6	25.5	31.6	25.1	30.5	24.7	1593	883
YOKOSUKA	1.9	2.9	34.1	25.9	32.1	25.2	30.8	24.8	1397	938
YOKOTA AB	–3.8	–2.7	34.0	25.8	32.8	25.4	31.2	24.6	1982	774
Jordan										
AMMAN	1.1	2.7	36.0	18.6	34.2	18.3	33.1	18.1	1192	1147
IRBID MET	1.7	3.3	34.4	19.6	32.9	19.4	31.7	19.3	1097	1070
QUEEN ALIA INTL	–0.8	0.7	37.0	19.8	35.2	19.0	34.1	18.9	1354	829
Kazakhstan										
ALMATY	–20.2	–17.2	34.2	18.4	32.7	18.0	31.0	17.6	3586	477
ASTANA INTL	–32.8	–30.0	32.3	17.7	30.2	17.2	28.4	16.8	5735	191
KARAGANDY INTL	–32.7	–29.1	32.0	16.7	30.1	16.3	28.2	15.6	5624	166
PAVLODAR	–34.9	–31.5	33.0	18.4	31.0	18.2	29.1	17.6	5726	246
SHYMKENT	–16.2	–13.0	37.8	19.0	36.2	18.6	35.0	18.3	2581	864
TARAZ	–20.1	–16.9	35.8	17.9	34.2	17.6	32.8	17.3	3178	608

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
Kenya										
MOMBASA INTL	20.1	20.8	33.1	25.1	32.6	25.1	32.1	25.0	0	3036
NAIROBI JOMO KENYATTA INTL	10.0	11.2	29.0	15.8	28.2	15.8	27.4	16.0	84	590
Korea, Democratic People's Republic of										
CHONGJIN	–12.4	–10.9	27.4	22.6	26.2	22.0	25.1	21.5	3776	232
HAMHUNG	–12.9	–11.0	31.5	23.9	29.9	23.4	28.4	22.6	3187	423
KAESONG	–12.8	–10.9	30.9	25.2	29.6	24.3	28.4	23.6	3061	570
NAMPO	–12.8	–10.9	30.2	25.5	29.1	24.7	28.0	24.0	3163	583
PYONGYANG SUNAN INTL	–14.7	–12.7	31.2	24.4	30.1	23.9	29.0	23.3	3243	619
SINUIJU	–15.5	–13.6	30.9	24.1	29.5	23.4	28.2	22.9	3481	525
WONSAN	–10.2	–8.4	31.7	23.5	30.1	23.0	28.5	22.6	2918	457
Korea, Republic of										
BUSAN	–5.0	–3.3	31.2	25.4	30.1	25.1	29.0	24.7	1862	717
BUSAN GIMHAE INTL	–6.1	–4.9	32.9	25.9	31.2	25.4	30.1	24.8	2098	786
CHANGWON	–5.0	–3.4	32.4	25.4	31.1	25.1	29.9	24.5	1968	797
CHEONGJU	–10.7	–8.8	32.8	24.6	31.5	23.8	30.3	23.1	2657	755
CHEONGJU INTL	–13.2	–11.1	33.1	26.2	32.0	25.3	30.8	24.6	2850	724
DAEGU	–6.9	–5.3	34.3	24.1	32.9	23.7	31.6	23.2	2185	862
DAEGU AB	–8.1	–6.8	34.8	25.4	33.1	24.8	31.9	24.2	2329	823
DAEJEON	–10.7	–8.8	32.5	25.2	31.2	24.4	30.0	23.6	2682	696
GIMPO INTL	–13.2	–11.2	32.1	24.8	30.9	24.4	29.8	23.5	3002	654
GWANGJU	–6.5	–5.0	32.6	25.0	31.4	24.5	30.3	23.9	2261	812
GWANGJU INTL	–7.1	–5.8	34.1	26.3	32.9	25.6	31.2	24.8	2386	838
INCHEON	–10.2	–8.3	31.0	24.7	29.7	24.1	28.6	23.4	2701	638
JEJU	0.4	1.3	32.0	25.3	31.0	25.2	30.0	25.0	1647	823
JEJU INTL	–0.1	1.0	32.0	26.2	30.9	26.4	29.9	26.0	1760	760

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
JEONJU	–8.7	–6.9	33.2	24.9	32.1	24.4	30.8	23.6	2437	817
JINJU	–8.5	–7.0	33.0	24.8	31.7	24.4	30.4	23.9	2392	724
OSAN AB	–13.1	–11.1	33.0	26.3	31.8	25.5	30.2	24.5	2874	709
POHANG	–7.1	–5.8	34.0	25.9	32.7	25.4	31.0	24.8	2237	686
PYEONGTAEK A511	–12.6	–10.8	32.9	25.8	31.2	24.9	30.1	24.2	2873	701
SEOGWIPO	0.5	1.7	31.5	26.4	30.6	26.2	29.7	25.8	1384	905
SEOUL AB	–14.8	–12.0	33.2	25.3	31.9	24.6	30.2	23.5	2911	671
SEOUL CITY	–11.4	–9.3	32.1	24.1	30.9	23.3	29.7	22.7	2684	736
SEOUL SINYONGSAN	–11.8	–10.1	33.2	25.2	32.0	24.5	30.8	24.1	2620	796
SUWON	–11.3	–9.4	32.2	25.0	30.9	24.2	29.7	23.5	2773	712
ULSAN	–5.8	–4.3	33.2	24.8	31.9	24.5	30.5	24.0	2083	724
WANDO	–3.9	–2.5	31.3	25.9	30.1	25.4	29.0	24.8	2096	706
YEOSU	–4.7	–3.3	30.4	25.1	29.4	24.7	28.4	24.4	2018	696
Kyrgyzstan										
BISHKEK	–17.9	–14.9	35.2	19.2	33.7	18.4	32.3	17.9	3019	640
Latvia										
RIGA	–19.2	–15.1	28.9	20.1	27.0	19.7	25.1	18.3	4123	93
Lebanon										
BEIRUT RAFIC HARIRI INTL	8.1	9.5	32.6	23.4	31.3	24.2	30.8	24.3	399	1493
Libyan Arab Jamahiriya										
BENINA INTL	6.8	7.8	37.1	20.7	35.2	20.5	33.7	20.2	606	1363
MISRATA	8.3	9.2	36.9	21.5	34.5	21.4	32.5	21.6	448	1408
TRIPOLI INTL	4.6	5.8	42.0	22.9	39.9	22.3	38.0	21.9	631	1687
Lithuania										
KAUNAS	–18.7	–15.3	28.4	19.9	26.6	18.9	24.8	17.9	4100	84
VILNIUS INTL	–19.3	–16.0	28.7	19.3	26.8	18.5	25.0	17.6	4273	88

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	**99.6%**	**99%**	**DB / MCWB**		**DB / MCWB**		**DB / MCWB**		**HDD / CDD 18.3**	
Macao										
MACAU INTL	7.4	9.0	32.9	27.0	32.1	26.9	31.2	26.8	282	2014
Macedonia, the former Yugoslav Republic of										
SKOPJE ALEXANDER THE GREAT	–12.0	–8.2	36.0	20.3	34.2	20.1	32.8	19.6	2568	547
Madagascar										
IVATO	8.0	9.0	29.9	19.7	29.0	19.7	28.1	19.7	294	721
Malaysia										
KOTA KINABALU INTL	22.8	23.0	33.8	28.0	33.2	27.7	32.9	27.5	0	3491
KUALA LUMPUR SUBANG	22.7	23.0	34.8	26.3	34.1	26.1	33.8	26.1	0	3683
KUANTAN	21.7	22.1	34.1	26.8	33.4	26.7	33.0	26.6	0	3358
KUCHING INTL	22.0	22.4	34.0	25.9	33.2	25.9	32.9	25.9	0	3277
SANDAKAN	22.9	23.3	33.8	26.5	33.1	26.4	32.5	26.4	0	3466
TAWAU	22.1	22.7	32.7	26.0	32.2	26.1	31.9	26.1	0	3245
Mali										
BAMAKO-SENOU INTL	14.9	16.2	40.2	19.7	39.6	19.9	38.8	20.0	0	3516
Mauritania										
NOUAKCHOTT	12.9	14.1	41.2	20.2	39.6	20.1	37.8	20.0	2	2986
Mexico										
ACAPULCO INTL	19.2	20.8	33.2	26.6	33.1	26.6	32.8	26.4	0	3280
CANCUN INTL	13.2	14.9	34.0	27.0	33.2	26.8	32.9	26.7	3	2858
CHETUMAL INTL	15.6	17.4	34.1	26.8	33.4	26.8	32.8	26.7	0	3259
GUADALAJARA INTL	1.9	3.1	33.2	15.8	32.2	15.4	31.2	15.0	352	721
GUANAJUATO INTL	4.0	5.9	34.1	14.7	33.0	14.7	31.9	14.7	267	794
HERMOSILLO INTL	4.8	6.2	42.8	22.8	41.4	23.0	40.2	22.8	211	2682
MAZATLAN INTL	8.2	9.9	34.0	25.5	33.2	25.3	32.9	25.2	31	2131
MERIDA INTL	13.8	15.8	38.8	24.3	37.2	24.4	36.2	24.4	1	3276

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
MEXICO CITY INTL	3.1	4.9	29.1	12.6	28.1	12.4	27.0	12.3	581	204
MONTERREY INTL	3.1	5.0	38.8	23.0	37.8	22.9	36.8	23.1	370	2142
PUERTO VALLARTA INTL	14.1	15.2	33.2	26.8	33.1	26.8	32.8	26.7	1	2572
SAN LUIS POTOSI INTL	0.4	2.2	32.2	14.7	31.0	14.8	29.8	14.8	667	431
TAMPICO INTL	10.2	12.0	34.1	26.7	33.2	26.6	33.0	26.6	77	2561
TAPACHULA	20.0	20.9	35.4	26.0	34.8	26.0	34.2	25.9	0	3482
TIJUANA INTL	5.8	6.8	32.2	20.3	30.2	19.8	28.9	19.4	704	505
TOLUCA INTL	–2.0	–0.9	26.1	12.1	25.0	11.9	24.0	11.7	1776	2
TORREON INTL	3.8	5.7	38.0	20.6	36.9	20.4	35.9	20.2	315	2048
VERACRUZ INTL	14.8	16.0	35.1	26.8	34.1	26.8	33.2	26.6	3	2743
Moldova, Republic of										
CHISINAU	–14.3	–11.5	32.5	19.8	30.6	19.4	29.0	18.8	3199	399
Mongolia										
CHINGGIS KHAAN INTL	–36.1	–33.9	31.0	15.7	28.8	15.0	26.7	14.3	7049	98
Morocco										
AGADIR AL MASSIRA INTL	5.0	6.1	38.8	19.9	35.0	19.1	32.1	19.0	393	938
CASABLANCA ANFA	6.4	7.6	29.7	21.5	27.6	21.8	26.2	21.8	636	648
CASABLANCA MOHAMMED V INTL	3.0	4.2	35.9	21.4	33.1	21.3	31.1	21.0	816	791
FES-SAISS	0.8	2.0	39.6	19.9	37.6	19.9	35.8	19.7	1201	876
INEZGANE	5.0	6.5	35.2	19.4	31.8	18.8	29.0	18.4	522	649
MARRAKECH MENARA	4.0	5.2	42.0	20.6	39.9	20.5	37.9	20.3	620	1430
MEKNES BASSATINE	2.3	3.8	39.0	20.9	36.8	20.8	34.8	20.5	1097	869
OUJDA ANGADS	0.9	2.2	37.9	20.6	35.9	20.7	34.0	20.4	1111	898
RABAT SALE INTL	4.8	5.9	32.9	21.5	30.0	21.2	28.0	21.4	802	545
TANGIER IBN BATOUTA	4.1	5.8	33.2	21.4	31.9	21.3	30.2	21.1	793	731
TETOUAN SANIA RAMEL	6.1	7.6	33.0	20.4	31.1	20.4	29.7	20.4	626	836

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB	MCWB	DB	MCWB	DB	MCWB	HDD	CDD 18.3
Mozambique										
MAPUTO INTL	11.9	13.0	35.4	23.7	33.7	23.7	32.1	23.7	17	1978
Netherlands										
AMSTERDAM SCHIPHOL	–6.2	–4.2	27.8	19.8	25.6	19.0	23.7	18.0	2929	71
HOEK VAN HOLLAND	–5.2	–3.3	27.2	19.3	24.7	18.4	22.8	18.0	2757	70
IJMUIDEN	–6.4	–4.1	25.6	18.7	23.6	17.8	21.8	17.6	2921	51
ROTTERDAM THE HAGUE	–6.2	–4.1	28.1	19.9	25.8	19.1	24.0	18.1	2902	71
VALKENBURG	–6.3	–4.2	27.1	19.6	24.8	18.7	22.9	17.8	2941	56
WOENSDRECHT AB	–7.6	–5.2	29.1	19.8	26.7	19.1	24.8	18.2	2963	78
New Zealand										
AUCKLAND AERO AWS	4.4	5.6	25.2	19.7	24.3	19.2	23.5	18.8	1222	157
AUCKLAND INTL	4.0	5.2	25.7	19.9	24.8	19.4	23.8	18.9	1218	172
CHRISTCHURCH AP AWS	–2.4	–1.4	27.6	16.6	25.5	15.8	23.5	15.2	2597	49
CHRISTCHURCH INTL	–2.8	–1.9	28.0	16.9	25.9	16.0	23.9	15.4	2619	56
Nicaragua										
MANAGUA INTL	20.0	20.9	36.0	24.3	35.1	24.2	34.8	24.1	0	3479
Niger										
NIAMEY DIORI HAMANI INTL	15.9	17.0	42.3	20.5	41.8	20.4	40.9	20.5	0	4249
Norway										
HAKADAL	–19.1	–16.1	26.5	17.6	24.8	16.9	23.0	15.9	4513	44
OSLO-BLINDERN	–14.3	–12.1	26.7	17.3	24.8	16.6	23.1	15.7	4182	54
Oman										
AL BURAIMI	9.8	11.2	45.1	21.5	44.1	21.3	43.1	21.2	71	3756
Pakistan										
BENAZIR BHUTTO INTL	2.1	3.2	41.1	22.7	39.4	22.8	38.0	22.7	639	2044
JINNAH INTL	10.1	11.8	38.9	22.7	37.1	23.1	36.0	23.5	24	3248

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
LAHORE ALLAMA IQBAL INTL	3.0	4.8	43.2	23.4	41.9	23.3	40.1	23.3	444	2608
Palestinian Territory, Occupied										
JERUSALEM ATAROT	0.8	2.2	33.1	18.3	31.8	18.3	30.3	18.1	1293	789
Panama										
PANAMA PACIFICO INTL	22.2	22.9	35.0	25.4	34.1	25.3	33.8	25.2	0	3566
TOCUMEN INTL	20.9	21.6	34.1	25.3	33.4	25.1	33.0	24.9	0	3363
Paraguay										
SILVIO PETTIROSSI INTL	5.1	7.1	37.1	23.9	36.1	24.0	35.1	24.1	257	2109
Peru										
AREQUIPA INTL	6.0	6.8	24.1	11.4	23.2	11.0	23.0	10.8	1138	2
CHICLAYO INTL	14.9	15.2	32.2	24.2	31.8	24.0	30.9	23.5	1	1626
CUSCO INTL	0.1	1.1	23.0	10.1	22.2	9.9	21.7	9.8	2001	0
HUANCHACO INTL	14.3	14.8	28.0	23.4	27.1	23.0	26.2	22.3	131	671
IQUITOS INTL	19.0	20.2	34.1	26.4	33.7	26.4	33.0	26.3	0	3057
LIMA CALLAO INTL	14.0	14.4	28.8	22.7	27.8	22.2	26.9	21.9	182	779
PIURA INTL	15.9	16.4	34.0	25.4	33.2	25.1	32.7	24.8	0	2386
PUCALLPA INTL	17.8	19.0	34.9	26.2	34.1	26.1	33.5	26.0	1	3142
Philippines										
CAGAYAN DE ORO	22.1	22.8	34.6	27.5	34.1	27.4	33.6	27.3	0	3601
FRANCISCO BANGOY INTL	22.8	23.1	34.0	26.9	33.2	26.8	33.0	26.8	0	3552
GENERAL SANTOS INTL	22.7	23.0	35.0	27.3	34.3	27.1	33.8	27.0	0	3553
ILOILO	22.8	23.3	34.8	27.6	34.1	27.6	33.4	27.4	0	3560
MACTAN CEBU INTL	23.3	23.8	33.1	27.3	32.6	27.1	32.2	27.0	0	3533
MANILA	23.1	23.8	34.6	26.4	33.9	26.4	33.2	26.3	0	3727
NINOY AQUINO INTL	21.8	22.4	35.0	26.0	34.2	25.9	33.7	25.9	0	3548
SANGLEY POINT AB	22.3	23.4	35.1	28.5	34.4	28.3	33.8	28.1	0	3781

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	**99.6%**	**99%**	**DB / MCWB**		**DB / MCWB**		**DB / MCWB**		**HDD / CDD 18.3**	
SCIENCE GARDEN	20.3	21.1	35.1	26.3	34.5	26.2	33.7	26.2	0	3392
ZAMBOANGA INTL	22.7	23.2	34.1	27.5	33.7	27.4	33.2	27.2	0	3629
Poland										
GDANSK LECHA WALESY	–15.0	–12.0	27.2	19.1	25.2	18.2	23.8	17.5	3946	52
GDANSK-SWIBNO	–17.0	–12.7	25.8	19.5	23.6	18.3	21.9	17.6	3891	34
HEL	–9.1	–7.1	25.4	20.3	23.8	19.3	22.4	18.6	3590	58
KATOWICE	–14.9	–11.9	29.7	19.9	27.8	18.9	26.0	18.1	3669	107
KRAKOW BALICE	–15.8	–12.9	30.1	20.4	28.1	19.6	26.3	18.7	3626	129
LODZ	–14.7	–11.9	29.9	19.6	28.0	18.8	26.2	18.0	3694	127
LUBLIN RADAWIEC	–16.6	–13.3	29.1	20.2	27.2	19.6	25.4	18.6	3871	106
POZNAN LAWICA	–13.6	–10.6	30.2	19.4	28.3	18.6	26.7	18.0	3521	137
RACIBORZ	–15.1	–12.0	30.0	20.2	28.0	19.4	26.2	18.6	3501	122
SZCZECIN	–12.0	–9.0	29.1	20.0	27.1	19.1	25.3	18.4	3463	99
TERESPOL	–18.3	–14.6	29.8	20.4	27.8	19.7	26.1	18.6	3852	122
WARSZAWA OKECIE	–15.8	–12.4	30.0	20.3	28.0	19.3	26.2	18.3	3678	139
WROCLAW STRACHOWICE	–13.9	–10.7	30.3	20.0	28.4	19.2	26.7	18.5	3422	136
Portugal										
LISBOA	4.6	5.8	33.8	20.4	31.7	19.7	29.7	19.2	1032	568
Puerto Rico										
JOSE APONTE DE LA TORRE AP	20.2	21.1	32.2	25.8	31.9	25.6	31.2	25.4	0	3200
LUIS MUNOZ MARIN INTL	20.9	21.4	33.1	25.2	32.1	25.4	31.6	25.4	0	3162
Qatar										
DOHA INTL	11.8	13.0	44.0	22.2	42.9	22.4	41.8	22.8	57	3726
Romania										
BUCURESTI BANEASA	–13.1	–10.2	34.2	21.0	32.7	20.6	31.0	20.1	2993	410
BUCURESTI HENRI COANDA INTL	–13.9	–10.9	34.0	21.4	32.2	21.4	30.9	20.6	2952	444

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
CLUJ NAPOCA	–14.6	–11.8	31.0	20.3	29.2	19.7	27.7	19.0	3458	188
CONSTANTA	–9.0	–6.9	30.2	23.5	28.9	22.8	27.8	22.3	2573	476
CRAIOVA	–12.4	–9.7	34.1	21.3	32.3	20.9	30.7	20.5	2856	472
IASI	–15.8	–12.6	33.1	21.0	31.2	20.4	29.7	19.9	3206	362
MIHAIL KOGALNICEANU	–11.0	–8.9	33.0	21.6	31.1	21.0	29.8	20.7	2821	439
TIMISOARA TRAIAN VUIA	–11.6	–9.0	34.1	21.0	32.3	20.8	30.8	20.1	2839	381
Russian Federation										
ARKHANGELSK TALAGI	–32.8	–29.0	27.6	19.4	25.1	18.0	23.0	16.9	6216	47
ASTRAKHAN	–18.9	–15.6	36.2	21.2	34.6	20.8	32.9	20.4	3357	703
BALANDINO	–29.1	–26.2	30.8	19.3	28.8	18.7	26.9	18.0	5564	147
BARNAUL	–33.8	–30.6	30.1	18.8	28.4	18.3	26.9	17.6	5841	164
BOLSHOYE SAVINO	–30.8	–27.2	29.9	20.3	27.9	19.2	26.0	18.1	5740	110
BOLVANSKIY	–32.6	–30.6	14.0	11.6	11.8	10.3	9.8	8.7	8887	0
BRYANSK	–22.1	–18.8	29.2	19.8	27.3	18.6	25.7	17.9	4503	128
CHEREPOVETS	–29.6	–26.3	28.3	20.0	26.2	19.0	24.2	17.9	5514	56
CHERTOVITSKOYE	–24.2	–21.0	32.9	19.2	30.6	18.7	28.2	18.0	4376	214
CHITA KADALA	–37.3	–35.2	31.0	19.1	28.9	18.1	27.0	17.1	7008	102
GUMRAK	–22.4	–19.7	35.3	18.7	33.3	18.5	31.3	18.1	4071	471
IRKUTSK	–35.6	–32.1	28.8	17.8	26.9	17.5	25.1	16.7	6607	53
IZHEVSK	–29.3	–26.1	29.6	19.9	27.7	18.9	26.0	18.1	5642	124
KALUGA	–25.3	–21.8	28.4	19.3	26.7	18.6	25.0	18.1	4847	78
KAZAN	–27.8	–24.5	30.9	19.9	28.8	19.3	26.9	18.4	5230	182
KEMEROVO	–33.9	–30.9	28.9	19.0	27.1	18.2	25.2	17.4	6213	114
KHABAROVSK	–30.1	–28.2	30.3	22.4	28.8	21.7	27.1	20.8	6059	227
KHRABROVO	–16.4	–13.0	28.1	19.9	26.1	18.8	24.2	17.8	3825	73
KIROV	–29.0	–26.0	29.5	20.4	27.6	19.2	25.8	18.2	5592	126

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
KOLTSOVO	–30.7	–27.8	29.7	19.5	27.8	18.6	25.9	17.7	5873	96
KRASNODAR	–14.7	–11.1	34.4	22.4	32.8	22.0	31.0	21.3	2832	541
KRASNOYARSK	–33.7	–31.1	28.4	18.3	26.6	17.6	24.8	16.8	6254	68
KRASNOYARSK MININO	–36.6	–33.8	28.9	19.2	27.1	18.5	25.3	17.6	6166	102
KURGAN	–32.5	–29.4	31.4	19.2	29.4	18.8	27.6	18.2	5842	168
KURSK	–22.1	–19.1	30.8	19.6	28.8	18.8	27.0	18.2	4352	205
KURUMOCH	–26.8	–23.5	32.2	19.3	30.2	18.8	28.4	18.2	4948	244
MAGNITOGORSK	–29.6	–27.0	30.7	18.5	28.8	17.8	27.0	17.2	5748	145
MAKHACHKALA	–12.6	–9.4	31.6	23.1	30.3	23.2	29.1	22.9	2746	582
MOSCOW BIBIREVO	–22.2	–19.0	29.7	20.9	27.8	20.1	25.9	19.1	4629	138
MOSCOW SHEREMETYEVO	–24.0	–20.9	30.0	19.1	28.0	18.5	26.0	18.0	4856	120
MOSCOW VNUKOVO	–23.2	–20.1	29.8	19.4	27.9	18.7	25.9	18.1	4813	128
MURMANSK	–32.2	–29.0	24.2	16.1	21.9	14.9	19.6	13.9	6660	10
NIZHNY NOVGOROD STRIGINO	–26.8	–23.3	30.1	20.1	28.2	19.4	26.3	18.6	5024	134
NIZHNY TAGIL	–31.2	–28.6	28.3	19.4	26.5	18.4	24.9	17.5	6095	62
NOVOKUZNETSK	–33.1	–30.2	29.3	19.4	27.6	18.6	25.9	18.0	5942	105
NOVOSIBIRSK TOLMACHEVO	–36.1	–32.9	29.8	18.9	28.0	18.2	26.2	17.4	6168	122
OMSK	–33.0	–30.2	31.0	18.8	29.1	18.2	27.2	17.6	6041	163
ORENBURG	–29.8	–26.3	34.7	19.5	32.7	19.0	30.6	18.4	5088	319
ORYOL	–23.6	–20.2	30.4	20.0	28.4	19.4	26.6	18.5	4480	166
PENZA	–27.2	–23.9	32.0	20.0	29.8	19.5	27.9	18.7	4912	188
PSKOV	–23.1	–19.2	28.7	20.3	26.8	19.2	25.0	18.1	4536	86
ROSTOV-NA-DONU	–17.6	–14.9	34.9	21.3	32.9	21.0	31.0	20.2	3401	512
RYAZAN	–24.2	–21.1	30.3	19.9	28.2	19.1	26.4	18.3	4747	157
SARATOV TSENTRALNY	–23.6	–20.8	33.2	19.9	31.1	19.3	29.1	18.8	4488	361
SMOLENSK	–22.1	–19.0	27.9	19.9	26.2	18.9	24.5	18.1	4685	83

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
SOCHI INTL	–1.9	–0.4	30.8	23.9	29.2	23.4	28.2	23.0	1951	509
ST PETERSBURG PULKOVO	–22.8	–19.7	28.2	19.6	26.2	18.6	24.3	17.7	4753	71
STAVROPOL INTL	–17.9	–14.2	33.6	19.6	31.8	19.2	29.9	18.8	3334	408
SURGUT	–40.2	–37.5	28.9	18.6	27.0	17.7	24.8	17.2	7392	83
TOMSK	–36.3	–33.2	28.6	19.7	26.9	18.8	25.3	18.0	6388	98
TRUBCHEVSK	–22.8	–19.4	30.0	20.5	28.0	19.6	26.2	19.0	4377	135
TULA	–24.6	–21.3	30.0	20.0	28.0	19.1	26.4	18.5	4717	139
TVER	–25.0	–21.7	29.5	19.5	27.4	18.9	25.5	18.0	4870	107
TYUMEN	–32.1	–29.3	29.5	19.6	27.8	18.8	26.1	18.1	5999	118
UFA	–31.2	–28.0	31.3	20.5	29.6	19.8	27.8	19.0	5448	161
ULAN-UDE	–36.7	–34.0	31.5	18.2	29.2	17.6	27.3	16.9	6882	136
VELIKIYE LUKI	–22.5	–19.0	28.0	19.2	26.4	18.7	24.7	18.0	4592	74
VLADIKAVKAZ	–14.6	–11.6	30.9	20.3	29.1	19.9	27.4	19.2	3370	267
VLADIMIR	–25.4	–22.4	29.5	20.8	27.4	20.0	25.6	19.1	4982	127
VLADIVOSTOK	–25.2	–22.6	28.2	21.3	26.7	20.5	24.9	19.9	4974	166
VORONEZH	–23.5	–20.4	32.4	20.1	30.4	19.5	28.4	18.7	4251	277
YELABUGA	–28.7	–25.5	31.0	20.4	28.8	19.7	27.0	18.6	5319	176
Saudi Arabia										
ABHA	6.5	7.8	31.2	13.2	30.8	13.2	29.9	13.3	480	819
DHAHARAN KING ABDULAZIZ	7.9	9.1	45.2	23.4	44.1	23.4	43.0	23.3	173	3437
GASSIM PRINCE ABDULAZIZ	3.2	5.2	45.0	20.7	44.1	19.9	43.1	19.4	412	2993
JEDDAH KING ABDULAZIZ INTL	15.8	16.8	41.0	23.7	39.9	24.2	38.8	24.6	1	3813
KHAMIS MUSHAIT KING KHALED AB	7.3	8.8	32.0	15.4	31.2	15.2	30.8	15.1	313	1042
MAKKAH	16.3	17.8	45.2	24.4	44.1	24.2	43.1	24.2	1	4830
MEDIAN PRINCE ABDULAZIZ INTL	9.1	10.9	45.2	19.1	44.2	18.8	43.2	18.5	76	3803
RIYADH KING SALMAN AB	5.9	7.8	44.7	19.3	43.9	18.9	43.0	18.6	276	3366

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
TABUK	1.9	3.1	41.1	18.9	39.9	18.4	38.8	18.0	657	2133
Senegal										
LEOPOLD SEDAR SENGHOR INTL	16.8	17.2	32.2	23.1	31.2	25.0	30.9	25.3	0	2420
Serbia										
BEOGRAD	–8.8	–6.7	34.3	21.3	32.6	21.0	30.9	20.3	2447	554
BEOGRAD SURCIN	–10.2	–8.0	34.4	21.2	32.8	21.3	31.0	20.5	2633	456
Singapore										
SINGAPORE CHANGI INTL	23.1	23.8	33.2	26.4	32.9	26.4	32.2	26.3	0	3605
Slovakia										
BRATISLAVA-STEFANIK	–10.8	–8.1	32.3	20.6	30.7	19.9	28.9	19.2	2992	297
South Africa										
BLOEMFONTEIN INTL	–5.0	–3.7	33.8	15.5	32.4	15.4	31.2	15.4	1392	503
CAPE TOWN INTL	3.9	5.2	31.6	19.7	29.8	19.2	28.0	18.7	874	412
DE AAR	–0.7	0.6	34.7	16.0	33.6	15.9	32.5	15.7	1138	762
DURBAN INTL	9.1	10.3	30.4	23.9	29.4	23.5	28.7	23.3	141	1102
EAST LONDON	7.9	9.0	30.6	20.0	28.8	20.5	27.2	20.7	415	579
JOHANNESBURG INTL	0.1	2.0	29.0	14.9	27.9	15.0	26.9	15.3	1094	268
PORT ELIZABETH INTL	5.2	6.8	29.2	18.9	27.4	19.5	26.1	19.8	663	401
PRETORIA	2.9	4.0	32.3	17.3	31.1	17.2	30.1	17.3	589	864
Spain										
A CORUNA	4.5	5.7	25.8	19.1	24.1	18.5	22.8	18.0	1397	122
ALICANTE	3.3	4.7	32.7	21.2	31.2	21.6	30.2	21.8	898	885
BARCELONA EL PRAT	1.6	2.9	30.8	23.6	29.6	23.4	28.7	23.1	1302	646
BILBAO	–0.2	1.1	32.2	20.8	29.8	20.2	27.8	19.6	1522	357
GRAN CANARIA	13.8	14.3	30.2	19.8	28.5	20.1	27.3	20.6	63	1092
MADRID BARAJAS	–3.9	–2.4	36.5	18.7	35.2	18.2	33.9	17.9	1971	657

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB	MCWB	DB	MCWB	DB	MCWB	HDD	CDD 18.3
MALAGA	4.1	5.5	35.1	20.1	33.0	20.2	31.0	19.9	809	887
MURCIA	2.5	3.9	36.0	21.8	34.7	21.6	33.4	21.6	884	1120
PALMA DE MALLORCA	0.2	1.8	33.1	22.5	31.8	22.6	30.6	22.5	1263	711
SEVILLA	2.0	3.5	39.2	22.3	37.9	21.8	36.2	21.1	848	1232
TORREJON AB	–4.8	–3.1	36.2	19.7	35.0	19.0	33.8	18.4	2099	594
VALENCIA	0.8	2.1	33.2	20.9	31.9	21.4	30.8	21.6	1088	834
VALLADOLID	–3.8	–2.6	34.3	18.2	32.7	17.8	30.9	17.4	2395	362
ZARAGOZA AB	–2.2	–0.9	36.2	21.2	34.7	20.7	32.9	20.1	1703	709
Sri Lanka										
BANDARANAIKE INTL	21.0	22.0	33.1	24.6	32.3	25.2	32.0	25.3	0	3405
Sweden										
GOTEBORG	–12.0	–9.5	26.8	18.1	25.2	17.7	23.5	16.8	3619	63
MALMO	–9.7	–7.3	26.5	18.9	24.9	18.4	23.2	17.6	3506	47
STOCKHOLMN BROMMA	–15.0	–11.9	27.0	17.9	25.2	17.1	23.7	16.5	4149	55
UPPSALA	–18.8	–15.4	26.7	18.5	24.9	17.5	23.1	16.7	4477	31
Switzerland										
BERN-ZOLLIKOFEN	–9.8	–7.7	29.7	19.4	27.9	19.0	26.1	18.2	3349	128
LAEGEREN	–10.7	–8.6	26.3	17.4	24.5	16.7	23.0	16.2	3889	71
ZUERICH-FLUNTERN	–8.3	–6.3	29.1	19.3	27.3	18.6	25.6	17.9	3198	149
Syrian Arab Republic										
ALEPPO INTL	–2.1	–0.8	39.3	19.9	37.9	19.7	36.3	19.7	1496	1395
DAMASCUS INTL	–3.4	–1.8	39.7	18.7	38.1	18.3	36.9	18.1	1438	1169
DARAA	0.8	2.3	36.2	19.3	34.8	19.5	33.4	19.6	1139	1087
HAMA	–1.2	0.3	39.3	20.9	37.7	20.6	36.4	20.2	1281	1415
LATAKIA	4.0	5.4	32.8	22.5	31.8	23.8	30.9	24.2	712	1202
Taiwan										

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	**99.6%**	**99%**	**DB / MCWB**		**DB / MCWB**		**DB / MCWB**		**HDD / CDD 18.3**	
GANGSHAN	9.9	11.2	33.2	27.2	32.9	27.1	32.1	26.9	79	2262
HENGCHUN	16.0	16.9	32.6	26.8	32.1	26.7	31.7	26.6	6	2634
HSINCHU	9.1	10.2	33.1	27.9	32.6	27.7	32.1	27.5	276	1846
HSINCHU CITY	9.1	10.4	33.2	26.7	32.5	26.5	31.9	26.4	267	1812
KAOHSIUNG	12.9	14.1	32.7	27.1	32.2	27.1	31.7	26.9	31	2542
KAOHSIUNG INTL	12.1	13.6	33.2	26.7	33.0	26.6	32.2	26.4	32	2610
KEELUNG	10.5	11.5	33.9	25.9	33.0	25.8	32.2	25.8	237	1842
KINMEN	7.1	8.1	32.9	28.5	32.1	28.1	31.6	27.9	497	1592
MATSU NANGAN	4.5	5.6	31.6	27.7	30.9	27.5	30.0	27.1	997	1197
PINGTUNG NORTH	11.1	12.7	34.4	27.3	34.0	27.2	33.2	26.9	40	2511
PINGTUNG SOUTH	11.8	13.0	35.0	27.3	34.2	27.1	33.7	26.9	32	2623
TAICHUNG	8.0	9.2	34.2	27.8	33.9	27.8	33.1	27.5	181	2080
TAICHUNG AP	7.9	9.0	32.2	27.2	31.8	27.0	31.1	26.9	312	1652
TAINAN	10.2	11.8	33.5	27.7	33.0	27.6	32.3	27.3	73	2375
TAIPEI	9.8	11.0	34.9	26.9	34.1	26.7	33.4	26.4	219	2088
TAIPEI SONGSHAN	9.8	10.9	35.1	26.5	34.2	26.5	33.8	26.4	218	2114
TAIWAN TAOYUAN INTL	9.1	10.2	34.8	26.7	33.9	26.9	33.0	26.7	264	1941
TAOYUAN	8.7	9.8	34.0	28.2	33.2	27.9	32.7	27.7	330	1807
WU-CHI OBSERVATORY	10.3	11.4	32.9	27.4	32.3	27.2	31.8	27.0	193	1986
Tajikistan										
DUSHANBE	–9.8	–6.1	37.9	18.9	36.8	18.7	35.3	18.4	1943	927
Tanzania, United Republic of										
DAR ES SALAAM INTL	18.1	18.9	33.2	25.6	32.8	25.6	32.2	25.4	0	2955
Thailand										
BANGKOK INTL	19.6	21.0	37.2	26.3	36.4	26.4	35.8	26.4	0	3997
PHUKET	23.8	24.2	34.4	25.9	33.8	25.8	33.3	25.8	0	3807

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	**99.6%**	**99%**	**DB / MCWB**		**DB / MCWB**		**DB / MCWB**		**HDD / CDD 18.3**	
Togo										
LOME-TOKOIN	21.6	22.2	33.2	26.1	32.9	26.4	32.2	26.4	0	3421
Tunisia										
TUNIS-CARTHAGE INTL	5.1	6.3	37.8	22.5	35.8	22.5	34.0	22.3	751	1264
Turkey										
ADANA INCIRLIK	0.7	2.0	36.5	22.2	35.1	22.5	34.0	22.8	1033	1346
ADANA SAKIRPASA	1.1	2.9	36.8	22.2	35.1	23.0	34.1	23.3	919	1481
ANKARA ETIMESGUT	–11.0	–8.6	34.9	17.8	33.0	17.7	31.2	17.1	2801	444
ANTALYA	1.9	3.1	38.3	20.1	36.8	20.1	35.0	20.3	995	1289
BURSA	–3.2	–1.9	34.4	22.0	33.0	21.8	31.7	21.3	1914	667
DIYARBAKIR	–9.2	–6.1	40.2	19.2	39.1	19.1	38.0	19.0	2139	1214
ERZURUM	–29.1	–26.1	30.4	14.9	29.0	14.7	27.2	14.5	4941	81
ESENBOGA	–14.9	–11.2	33.9	17.2	32.0	16.9	30.2	16.5	3169	292
ESKISEHIR	–10.7	–8.2	33.2	19.2	31.8	18.8	30.1	18.2	2847	351
GAZIANTEP OGUZELI	–4.8	–3.1	39.1	21.1	37.8	20.6	36.3	20.1	1913	1179
ISTANBUL ATATURK	–1.8	–0.2	31.9	21.4	30.6	21.2	29.2	20.9	1811	714
IZMIR ADNAN MENDERES	–2.5	–1.0	37.1	20.7	35.8	20.4	34.5	20.1	1543	1032
IZMIR CIGLI	–1.8	–0.2	36.8	21.4	35.2	21.2	34.1	20.9	1352	1039
KAYSERI	–16.0	–12.4	34.4	17.3	32.8	16.9	31.0	16.4	3072	298
KONYA	–12.0	–9.2	34.2	16.5	32.8	16.4	31.1	16.0	2804	499
MALATYA ERHAC	–11.4	–8.8	38.0	19.4	36.8	18.6	35.2	18.3	2597	827
SAMSUN	–0.9	0.3	28.6	22.3	27.7	22.1	27.0	21.8	1888	444
VAN	–13.2	–11.3	29.0	18.6	27.8	18.6	26.9	18.4	3482	221
Turkmenistan										
ASHGABAT	–7.8	–4.9	40.2	19.5	39.1	19.4	37.9	19.3	1855	1509
Ukraine										

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	**99.6%**	**99%**	**DB / MCWB**		**DB / MCWB**		**DB / MCWB**		**HDD / CDD 18.3**	
CHERNIHIV	–19.4	–16.5	30.7	20.2	28.9	19.6	27.1	18.8	4023	197
DNEPROPETROVSK	–17.7	–14.9	33.6	21.0	31.5	20.3	29.8	19.7	3627	388
DONETSK	–18.8	–15.9	33.2	19.4	31.1	19.1	29.2	18.6	3784	334
KHARKIV INTL	–19.3	–16.6	32.8	19.7	30.6	19.0	28.9	18.6	3898	306
KHERSON	–15.5	–12.6	34.3	21.2	32.3	20.5	30.5	19.8	3221	441
KIEV ZHULIANY INTL	–17.0	–14.2	31.0	20.3	29.1	19.8	27.4	18.9	3757	239
KRYVYI RIH	–17.8	–14.9	33.2	20.5	31.2	19.8	29.6	19.2	3602	341
LUHANSK	–20.6	–17.2	34.7	20.6	32.6	20.1	30.6	19.5	3682	370
LVIV INTL	–17.0	–13.9	29.2	20.1	27.5	19.2	25.9	18.4	3817	118
MARIUPOL'	–15.8	–13.1	32.0	21.3	30.3	21.1	28.9	20.7	3461	415
ODESA INTL	–13.2	–10.2	32.3	20.6	30.8	20.2	29.0	19.8	3113	413
POLTAVA	–18.7	–15.8	31.8	20.2	29.9	19.5	28.2	18.9	3847	283
SIMFEROPOL INTL	–12.4	–9.8	33.5	20.3	31.8	19.9	29.9	19.3	2952	399
VINNYTSIA	–18.8	–15.3	29.7	19.6	27.9	18.9	26.4	18.3	3940	157
ZAPORIZHIA INTL	–17.5	–14.8	34.1	20.2	32.1	19.8	30.2	19.2	3524	399
United Arab Emirates										
ABU DHABI INTL	11.8	13.0	44.9	23.0	43.6	23.3	42.1	23.4	27	3676
AL AIN INTL	10.9	12.0	46.0	22.8	45.1	22.8	44.1	22.7	41	3967
BATEEN	13.6	14.8	44.1	23.3	42.8	23.6	41.2	24.0	13	3719
DUBAI INTL	13.1	14.2	43.1	23.5	41.8	23.8	40.5	24.2	16	3695
SHARJAH INTL	10.2	11.7	44.2	23.7	43.1	24.0	42.0	24.3	42	3492
United Kingdom										
AUGHTON	–2.9	–1.5	24.5	17.4	22.4	16.7	20.5	15.9	3193	18
BINGLEY NO2	–3.9	–2.7	23.7	17.3	21.7	16.2	19.9	15.3	3577	9
BIRMINGHAM	–4.9	–3.1	26.2	17.8	24.2	17.0	22.7	16.3	3102	31
BRISTOL	–3.2	–2.1	24.9	17.6	22.9	16.8	21.1	16.2	3060	21

Station	Heating DB		Cooling DB/MCWB 0.4%		Cooling DB/MCWB 1%		Cooling DB/MCWB 2%		Heat./Cool. Degree-Days	
	99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		HDD / CDD 18.3	
BRISTOL WEATHER CENTRE	–1.9	–0.5	26.7	18.3	24.8	17.2	23.0	16.6	2594	59
CARDIFF WEATHER CENTRE	–1.0	0.1	26.2	18.2	24.3	17.4	22.7	16.6	2530	57
CHURCH LAWFORD	–4.3	–2.8	26.4	18.6	24.3	17.5	22.6	16.6	3102	30
CILFYNYDD	–4.1	–2.6	25.5	18.0	23.4	16.8	21.5	16.1	3277	22
CROSBY	–3.4	–1.7	24.4	18.2	22.2	17.4	20.6	16.7	2906	19
EDINBURGH	–5.2	–3.2	22.1	16.6	20.7	16.0	19.2	15.1	3423	4
EMLEY MOOR	–3.3	–2.3	23.7	17.5	21.7	16.5	20.1	15.7	3494	14
GLASGOW	–6.0	–3.9	23.1	17.1	21.2	16.2	19.8	15.5	3376	7
GRAVESEND-BROADNESS	–2.4	–1.2	27.7	19.6	25.7	18.6	23.9	17.7	2612	74
HAWARDEN	–4.3	–2.7	25.1	18.2	23.1	17.4	21.5	16.6	3016	18
KENLEY	–3.2	–2.0	26.2	18.0	24.3	17.2	22.6	16.4	2977	42
LECONFIELD	–3.7	–2.1	24.9	18.2	23.1	17.3	21.6	16.5	3149	17
LEEDS BRADFORD	–3.8	–2.2	23.9	17.8	21.9	16.6	20.1	15.7	3434	12
LEEDS WEATHER CENTRE	–2.4	–1.2	26.2	17.9	24.1	17.0	22.4	16.1	2948	41
LIVERPOOL JOHN LENNON	–2.2	–1.1	25.0	17.7	23.0	16.9	21.2	16.3	2870	28
LONDON HEATHROW	–2.5	–1.2	28.3	18.6	26.2	17.7	24.5	17.0	2578	93
LONDON WC CLERKENWELL	–0.6	0.4	28.2	18.3	26.2	17.6	24.4	16.8	2322	123
MANCHESTER	–4.0	–2.2	25.5	17.8	23.4	16.9	21.8	16.2	3083	27
NORTHOLT	–3.8	–2.4	28.2	18.5	26.1	17.7	24.3	17.0	2747	71
NOTTINGHAM EAST MIDLANDS	–3.8	–2.1	26.2	18.0	24.1	17.0	22.2	16.2	3022	37
VALLEY ANGLESEY	–1.6	–0.3	22.9	17.3	20.8	16.1	19.1	15.4	2869	10
Uruguay										
CARRASCO INTL	1.1	2.8	31.8	21.9	30.0	21.4	28.2	21.0	1206	474
MONTEVIDEO PRADO	3.0	4.3	31.6	22.5	30.1	22.0	28.8	21.7	1104	573
Uzbekistan										
NAMANGAN	–9.0	–6.5	36.9	21.2	35.6	20.8	34.4	20.4	2235	1116

Appendix: Climatic Design Conditions for Selected Locations (*Continued*)

	Heating DB		Cooling DB/MCWB						Heat./Cool. Degree-Days	
			0.4%		1%		2%			
Station	**99.6%**	**99%**	**DB / MCWB**		**DB / MCWB**		**DB / MCWB**		**HDD / CDD 18.3**	
SAMARKAND	–10.7	–7.5	36.2	18.9	35.0	18.6	33.9	18.2	2217	856
TASHKENT INTL	–10.1	–7.6	38.7	19.7	37.2	19.2	36.0	18.9	2112	1057
Venezuela										
JUAN VICENTE GOMEZ INTL	19.9	20.7	35.2	23.4	34.7	23.3	34.0	23.2	0	3297
SIMON BOLIVAR INTL	20.8	21.6	34.0	28.1	33.1	27.7	32.8	27.6	0	3376
Viet Nam										
DA NANG INTL	16.7	17.5	36.2	26.1	35.2	26.1	34.2	26.2	3	2922
HAI PHONG PHU LIEN	9.7	10.8	33.9	28.8	33.0	28.6	32.3	28.2	179	2185
HO CHI MINH TAN SON NHAT INTL	20.0	21.1	35.6	25.8	34.8	25.8	34.0	25.7	0	3598
NOI BAI INTL	9.9	11.0	36.0	27.4	34.9	27.5	34.0	27.4	174	2381
Zimbabwe										
HARARE INTL	6.2	7.4	31.1	16.5	30.0	16.4	29.0	16.4	349	762

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